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Emitter Materials Study

Thermionic Energy Converters

FORD INSTRUMENT COMPANY
DIVISION OF SPERRY RAND CORPORATION

31-10 Thomson Avenue, Long Island City 1, N. Y.

Contract No. NONR-3696 (00)

Task No. 391-429

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FINAL TECHNICAL REPORT

December 31, 1962

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OFFICE OF NAVAL RESEARCH
Washington 25, D.C.

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CONTRACT Nonr 3696(00)

Task No. NR 391-429

FINAL TECHNICAL REPORT

EMITTER MATERIALS STUDY

THERMIONIC ENERGY CONVERTERS

NUCLEAR DEVELOPMENT DIVISION
FORD INSTRUMENT COMPANY
Division of Sperry Rand Corporation
Long Island City 1, N.Y.

December 31, 1962

FOREWARD

This report was initiated by the Power Branch, Office of Naval
Research, Washington 25, D.C. The research and development work upon
which this report is based was accomplished by the Nuclear Development
Division, Ford Instrument Company, Division of Sperry Rand Corporation,
Long Island City, New York, under the Office of Naval Research Contract
Nonr 3696(00) FBM, "Emitter Materials Study-Thermionic Energy Converters."
(Dr. John J. Connelly Jr. monitored the project for the Power Branch.)

The research and development was directed by M. Silverberg -
Engineering Department Head, and L. L. Haring - Project Supervisor.
The experiments and analysis were performed by J. Jacobs - Principal
Engineer, L. Phillips and M. Cosenza - Senior Engineers, and E. Berman -
Engineer. W. Franklin - Principal Engineer and R. Mercer - Assistant
Engineer were responsible for device fabrications.

ii.

<u>ERRATA</u>

EMITTER MATERIALS STUDY - THERMIONIC ENERGY CONVERTERS

FINAL TECHNICAL REPORT DEC. 31, 1962

CONTRACT NO. Nonr-3696(00)

TASK NO. 099 - 365

<u>Page</u>	<u>Line</u>	<u>Error</u>	<u>Correction</u>
Cover	8	Task No. NR 391-429	Task No. NR 099-365
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12	23	I vs V vs V	I vs V
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ABSTRACT

An experimental program was conducted on selected emitter materials to determine their potential for use in low temperature thermionic energy converters. One oxide emitter and four different dispenser types were evaluated in parallel plate and cylindrical geometry in both glass and metal ceramic construction. With respect to power density the various dispenser emitter types showed suitable and reasonably similar performance. Performance degradation was reversed in some of these diodes and its mechanism explored and explained.

NOMENCLATURE

B –   Philips Type Impregnated Tungsten Emitter
(See Appendix A for Chemical Composition)

CCC –   Sylvania Oxide Emitter (See Appendix A for
Chemical Composition)

d –   Interelectrode Spacing

E_m –   Emitter Material

S-70)
S-80)   Semicon Associates Type No. (See Appendix A for Chemical
S-85)   Composition)

TC –   Test Cell

T_c –   Collector Temperature

T_{cs} –   Cesium Temperature

T_e –   Emitter Brightness

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I. INTRODUCTION

The aim of this program was to select emitter materials together with appropriate geometries to determine their relative merits for use in low temperature thermionic energy converters. Extensive evaluations with these emitters were made of thermionic performance parameters such as output voltage, current, power density and resistance to poisoning. The interrelationship between specific emitter performance and environmental parameters was also substantiated. Most significantly, the mechanism of performance degradation and its reversal was explored and tentatively established.

II. ACCOMPLISHMENTS AND CONCLUSIONS

A. Significant Program Accomplishments

1. Four dispenser emitter materials were found to exhibit suitable performance in the 1100°C - 1150°C range for low temperature thermionic energy converters.

2. The first reported accomplishment of reversal of performance slump in an operating thermionic converter. The mechanism of this reversal has been explored and explained as a collector work function phenomena.

3. An extensive collection of emitter performance data has been compiled and correlated in connection with low temperature converters using various dispenser emitters, in both glass and metal ceramic construction.

4. Useful evaluation techniques have been devised and proven for obtaining reliable pulse performance data and variable collector heat in glass cells.

B. Conclusions

The four dispenser emitter materials evaluated are:

Philips Type "B"

Semicon #S-70

Semicon #S-80

Semicon #S-85

1. These have all demonstrated suitable performance in the 1100°C range for cesium plasma energy converters. The S-70 material has shown to have better power density at the lower temperature limit. It also has

better resistance to poisoning in both the processing and operating phases, because of its high barium production rate. The oxide coated emitter material which was tested was shown to be unsuitable for these devices because of its limited emission density.

2. The experiments determined that emitter poisoning was not a contributing factor to performance slump under our operating conditions. This resulted because of the high replenishment rate of barium on the surface of the emitter.

3. The cesium bath technique over the collector has demonstrated that slump is a collector poisoning phenomena. The suspected mechanism for collector cleanup is the dissolving and removing of cesium compounds by the liquid cesium bath. This buildup of cesium compounds is attributed to the long term outgassing of envelope materials at operating temperatures. For control of collector poisoning, extreme cleanliness with respect to potential outgassing constituents is required. Care must also be exercised as regarding purity of the original cesium charge and further contamination that may be introduced by virtue of the cesium release technique.

4. There is an interrelationship between the specific emitter performance and the converter environmental parameters.

a. Optimum collector temperatures for the parallel plate metal ceramic devices was found to be in the temperature range of 250°-350°C. In the cylindrical geometry devices the optimum temperature peak is at 450°C.

b. Increasing the spacing of the cylindrical devices from 0.100" to 0.175" showed considerable increase in power density.

c. The collector work function of any of the test diodes appeared to be unaffected by the wide range of emitter evaporation rates.

3.

C. Recommendations

      1. On the basis of the results of this program there are a number of suitable dispenser emitters for this temperature range. Further life testing is required to fully establish these relative merits.

      2. Further study of the sensitive parameters and mechanisms of the phenomena of performance degradation should be carried out.

      3. Inasmuch as slump appears to be a collector phenomenon, a study is warranted of the properties of various collector materials and their resistance to slump.

      4. These emitter materials and a number of others not studied under this program are deserving of further attention, especially under different conditions of operation, e.g., higher cesium pressure and closer spacing.

III. **EMITTER SELECTION CRITERIA**

Early in the program a survey was taken to determine the available data on types of emitter materials which could be suitable for low temperature thermionic devices. Table I summarizes the data obtained in this survey.

Furthermore, a number of desired goals for emitter materials for long lived, high performance, nuclear-thermionic applications were developed. This was used as a guide in evaluating the multitude of various emitters in the 1000°C - 1300°C range.

1. Electron Emission - A level of 10 amperes per square centimeter is required if one expects a useful power density from the converter. This figure will include cesium enhancement.

2. Life - The drop of emission over a 15,000-hour period should not exceed 10%.

3. Evaporant Material and Rate - High rates are associated with high emission while low rates usually reflect long life. But the most important effect is on the collector work function. In this case, the material evaporated is equally as important as the rate at which it leaves the emitter surface. As a result, methods for adjusting both the kind and quantity of evaporants must be considered.

4. Workability and Joining Properties - The ease of fabricating the material into the ultimate geometries required either by machining, spinning, drawing, pressing, etc., is extremely important. The capability of joining the emitter material to fuel surfaces, structural supports and lead surfaces by reasonable brazing and/or welding techniques must also be considered.

5. <u>Structural Strength</u> - The emitter materials will naturally be sub-
jected to vibration, impact, thermal shock, etc., at operating temperature. The
actual amplitude of the requirements will depend upon the reactor type and the
location at the converter assemblies. In-pile requirements will certainly vary
from out-of-pile installations. An example of this would be power excursion
pressure surges. It is realized, therefore, that only relative comparisons
of these properties between materials are possible at this time and that absolute
specifications (which are dependent upon the ultimate thermal design) are premature.

6. <u>Poisoning Resistance</u> - The emitter should not exhibit any deter-
ioration relative to cesium liquid or vapor. Also normal outgassing of converter
materials at operating temperature should not severely affect emission for
periods of 15,000 hours. Resistance to fission produce gas diffusion and n-α
reactions resulting in helium gas is important, but the necessary system information
is not yet available at this time.

7. <u>Radiation Resistance</u> - In order to discuss this criterion in a
reasonable manner, a short digression relative to converter location is necessary.
Thermionic converters can be incorporated into a nuclear reactor system in one
of three ways: in-pile, pile-surface, and out-of-pile. For marine power reactors,
in-pile or out-of-pile convertors appear possible.

The in-pile concept is one in which the thermionic cells are integrated
with the reactor fuel elements. For this concept fast reactors have been considered
by others for space application to achieve a minimum weight power plant and to re-
duce the poisoning effects of cell introduction. In such designs for power reactors
in the megawatt range, materials would be subjected to the fast neutron fluxes in
the order of 2×10^{14} n/cm^2 sec. In many Naval applications where thermal watercooled
reactors are used the fast reactor design problem of obtaining acceptable fuel

volume fractions is replaced by one of minimizing the amount of thermal neutron-capturing materials within the core. In a thermal design the fast neutron flux will be reduced to about 6×10^{13} neutrons/cm^2 sec, but the gamma dose rate from primary gammas and fission product gammas will be similar to that in fast reactors, between 5×10^8 to 1×10^9 R/hr. The level of thermal neutron flux will be of the order of 10^{14} neutrons/cm^2 sec, but it is realized that radiation damage is less severe with lower energy neutrons.

In out-of-pile systems the converters are removed from the reactor core and the emitters receive heat from the coolant in the primary loop. One advantage of this technique is the reduction in radiation environment. The gamma dose rate at the converter with a lithium coolant would be four to five decades lower than the in-pile case, while slow and fast neutron fluxes would be negligible from a materials point of view. The basic disadvantage of this system lies in the containment of corrosive liquid metals and metal salts at 1200°C temperatures necessary even for low temperature emitters.

8. <u>Availability</u> - A practical limitation on the choice of emitter materials for immediate application is procurement. Those materials which have an extensive background of statistical operating experience were heavily weighted in our selections for this program.

III. TEST CELL GEOMETRY AND PROCESSING

Three basic types of test cell configurations were chosen for the evaluation and comparison of the emitter materials selected. Test cells, employing glass envelopes, were constructed in both planar and cylindrical geometries as shown in Figures 1 through 6, respectively. Diodes of these types were found suitable for initial tests due to their ease and economy of manufacture although adequate parameter control, especially that of collector temperature control was not obtained with the same facility, as in a metal ceramic cell. However, some degree of collector temperature variation was accomplished (see Experimental Techniques). In addition, some two hundred (200) similar glass cells employing Philips types A and B emitters, during the past few years were made at the Ford Instrument Company, all of which form a good basis of comparison for new material in the same geometries.

The metal-ceramic construction with its external collector and more flexible electron gun design for emitter heating eliminated the above mentioned difficulties. Two such cells, TC-225 and TC-229 as shown in Figures 7 and 8 were fabricated with impregnated tungsten emitters manufactured by Semicon Associates, Inc., with the designation S-85. This material was selected for further evaluation in the metal-ceramic design after having shown promising performance early in the program. Again, as in the case of the glass cells, extensive comparison data was available on many metal-ceramic cells of the same geometry with the Philips Type "B" emitters.

Both geometries were used in the program. Some of the advantages of the cylindrical geometry used in the test cell were as follows:

8.

1. Better axial symmetry and reduced end effects

2. Better simulation of ultimate heat source configuration

3. Higher measured efficiencies possible in test cells

4. Minimum support emission phenomena

There are limitations, nevertheless, to cylindrical geometry, and these are:

1. Limitations in collector-emitter area ratios

2. Higher possibility of emitter-heater interactions. Consequently, both cylindrical and parallel plate geometries were evaluated and compared during the program.

Two basic similarities exist in the processing of all cells containing impregnated tungsten emitters. These emitters were pre-aged on the pump for approximately 100 hours at their activation temperature prior to tip-off and their collectors were heated to a temperature somewhat greater than 1300°C just before tip-off. Treating a cell collector this way, eliminated the heavy layer of emitter evaporants (Ba and BaO) (Ca and CaO) which would otherwise form on the collector due to the high initial emitter evaporation rate; this processing also brought the conditions of the emitter to such a point that subsequent emitter evaporation would occur at a considerably reduced rate. We found it desirable to hydrogen fire molybdenum parts at 1700° for 10 minutes prior to assembly.

At various times during the life of the cell on the pump, the condition of the emitter was checked by measuring its saturation current density by Shottky extrapolations. (See Figure 9).

After the final collector outgassing, the cell was allowed to

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cool, then the cesium ampule was broken. The cesium was slowly distilled from the ampule into the cell and the final tip-off was made. The composition of the cesium used is listed in the Appendix.

V. EXPERIMENTAL PROCEDURES AND TECHNIQUES

1. Instrumentation:

A) Emitter Heat Source:

In the planar and cylindrical glass cells evaluated, the operating temperature of the emitters was achieved by applying a 60 cycle half wave pulse to a heater which was inserted inside the cylindrical emitter. (See Figure 10A) The positive side of the heater was tied to the emitter so that the heater would be negative with respect to the emitter. This procedure minimized emission from the emitter to the heater.

In the metal ceramic cells evaluated, the emitters were heated by electron bombardment.

B) Firing Pulse with Time Delay for I vs V Characteristic:

During the off cycle of the heater, a period of 8 milli-seconds, a triangular pulse was used to fire the cell. (See Figure 10B) The pulse width and phase with respect to the on cycle of the heater was adjustable. The current vs voltage characteristic was measured only during the off cycle of the heater. This procedure eliminated side effects of such as ion storage in the cell due to heater voltage on during the duration of the collector firing pulse.

C) Collector Temperature Control:

In the glass cells, in order to determine the effect of varia-tion of collector temperature on the I vs V characteristic, a collector heat pulse was available. This pulse was square and had variable width so that the collector power could be controlled. This pulse occurred only during the on cycle of the heater, so that ion storage effects from this pulse, would not interfere with the true I vs V characteristic.

In the metal ceramic cell, the collector temperature was controlled by regulating the power input to a helical heater imbedded in a copper conductor-convector which was placed inside the collector cup. Thermocouple leads were attached in order to measure the collector temperature.

D) Cesium Temperature Control:

The glass cells were evaluated in a temperature controlled oven, the ambient temperature of the oven was recorded as the cesium temperature. Cesium temperature was varied by either raising or lowering the thermostat setting of the oven.

In the metal ceramic cells, the cesium temperature was controlled by regulating the power into a flexible heater tape which was wrapped around the cesium heat sink. An iron-constantan thermocouple was used as the sensor of a preset temperature controller which regulated the cesium temperature.

E) Emitter Brightness:

Emitter brightness was measured by means of an optical pyrometer and adjusted manually.

2. Test Procedures:

I vs V Characteristic:

Two methods were employed in establishing the current vs voltage characteristic of each device.

a) In the glass cells, I vs V vs V characteristics were determined using the circuitry shown in Figures 11 and 12 in the following manner. At a specified emitter temperature, collector temperature

and cesium temperature, the voltage developed across a current sensing, resistor was fed into the vertical axis of a Tektronix scope. The thermionic voltage developed across the cell itself was fed into the external sweep of the scope. In this manner, a curve of current versus voltage appeared across the screen. With the aid of a Dumont Scope camera and employing Polaroid 3000 film, permanent displays of the I vs V characteristics were recorded.

b) The metal ceramic cells were ignited using a variable DC supply with a one ohm load in series with the cell as shown in Figure 13. The procedure used in optimizing the output power was as follows. At a particular emitter brightness, the cell was fired by increasing the DC voltage available to the cell. An ammeter in series with the cell registered the output current. A 2000mv full scale voltmeter was connected between the collector and emitter.

Keeping the output current and the emitter brightness constant, the cell power output was optimized by first varying the cesium temperature and observing the cell voltage. The cesium temperature was raised or lowered until the output voltage of the cell was optimized. Then, keeping the cell current, emitter brightness and cesium temperature constant, the collector temperature was varied until the output voltage again reached a maximum. This procedure would then be repeated until the output voltage was maximum. Keeping the optimum collector temperature and the optimum cesium temperature constant the current could be varied from short circuit to a minimum and noting the output voltage. It was necessary to adjust the electron gun power in order to correct for changes in emitter temperature due to electron cooling.

13.

VI. <u>TEST RESULTS</u>

For each glass cell tested, which included planar and cylindrical geometries, current vs. voltage characteristics were taken using a time-varying collector trinagular wave form which plotted the current-voltage characteristic immediately on the oscilloscope. Extensive parameter studies were made in a short period of time using such a technique. Test cells #173, 178, 196, EC3, 240, 241, 242 and 243 were tested in this manner. Results are shown in Tables 2, 3, 4, 5, 8, 9, 10 and 11. Typical I vs V characteristics are shown in Figures 14 through 23.

In order to attain better parameter control in our evaluation, two metal-ceramic cells were designed and tested using the Semicon type S-85 emitter. The results of these cells were compared with a typical metal-ceramic cell employing the Philips type B emitter. DC data was taken on these cells, (TC-222, 225 and 229). The point by point DC method best simulates actual operating conditions although electron cooling effects and change in collector temperature due to variable electron heating must be adjusted at each point. Circuit diagram for this technique is shown in Figure 13. Experimental results are shown in Tables 6, 7 and 12.

TC-173:

TC-173 had reasonable vacuum pulsed emission, $\frac{17 \text{ amps}}{cm^2}$ although its output power as a thermionic converter was only $\frac{.24 \text{ watts}}{cm^2}$ at 1150° emitter brightness. This low output was probably due to severe collector contamination as a result of insufficient vacuum aging for an emitter (S-70) with such a high content of emitter impregnants. Cell geometry is shown in Figure 3.

14.

TC-178:

TC-178 delivered .6 watt/cm^2 at 1100°C emitter brightness but its performance does not compare with later S-70's (TC-242 and TC-243). TC-178 had a collector similar to TC-173 except that its length had been increased to 1-1/4". (See Figure 4) From the results of tests on these types of cells in the past it was apparent that good performance could be obtained at somewhat larger collector to emitter spacings with the additional benefit of lowering the minimum collector temperature by reducing the amount of energy per cm^2 intercepted by it. Consequently, cells were made with a collector to emitter psacing of .172" instead of .110" which was previously used. In addition, the collector length was increased to 1-1/2" and larger cooling fins were added (see Figure 5).

Two later cylindrical cells, TC-242 and TC-243 were fabricated and tested using the new collector configuration with the same size S-70 emitters. Resulting power densities of approximately 1 watt/cm^2 at emitter brightness as low as 1100°C were recorded.

TC-195:

TC-195 was a cylindrical cell fabricated with a Sylvania oxide emitter (55% Ba CO_3, 40% Sr CO_3, 5% Ca CO_3) coated on a 225 nickel alloy base designated CCC. Although this emitter did not appear suitable because of its low level of emission, it was readily available and tried. The cells thermionic output was negligible.

<u>TC-196:</u>

Planar cell TC-196 was fabricated with an impregnated tungsten emitter (Semicon S-85) which has a barium calcium aluminate mixture different from Philips Type B. (See Appendix for chemical composition).

A number of runs at different cesium and emitter temperatures were taken in order to survey the emitter's capability in our standardized planar geometry. Table 4 summarizes some of the pertinent data which showed encouraging possibilities. The use of a high voltage pulse on the collector in determining the I vs V characteristic of this cell probably gave a large degree of avalanching with accompanying high degree of ionization. This enhanced ionization at least in part was responsible for the high current density found here. In future tests such high pulses were avoided. In addition, the data below 1000°C is, somewhat optimistic due to cesium enhanced molybdenum skirt emission. At temperatures above 1100°C the skirt emission phenomenon should be negligible according to the Houston emission curves at 200°C bulb temperatures.

In order to completely avoid skirt emission, the next cell designed and tested had cylindrical geometry with negligible support area.

<u>TC-EC3:</u>

In order to explore more fully the characteristics of the Semicon S-85 (impregnated tungsten emitter) a cylindrical unit was fabricated and analyzed. Its geometry is shown in Figure 5.

The performance of the cell fell below that expected on the basis of the parallel plate unit (TC-196). In comparing the data shown in Table 5 and Figure 16 with TC-196 data, it was observed that the voltages of EC-3 were higher, while its current density was considerably lower. This indicated an increase in emitter work function. Subsequent emission checks showed this to be the case. The cause of this was assumed to be emitter poisoning which was verified by observing cesium oxide within the envelope.

16.

<u>TC-225 and TC-229:</u>

The results of TC-225 and TC-229 were similar to TC-222. The power density of TC-229 employing S-85 emitter was approximately 1.0 watt/cm^2 at 1150°C emitter brightness and cesium temperature 168°C. While, TC-222 employing the Philips type "B" emitter showed a power density of 1.11 watt/cm^2 at 1190° emitter brightness and 173° cesium temperature. Tables 6, 7 and 12 show the test results of the cells. Due to better collector temperature control, extensive parametric runs were made on TC-229. It was noted that at cesium temperature of 168°C and an emitter brightness of 1150°C, the power density fell off less than 10% for a collector temperature range from 258°C to 357°C. Also, with the collector temperature constant at 276°C and the emitter brightness at 1150°C, the power density decreased from .87 watts/cm^2 to .73 watts/cm^2 as the cesium temperature was varied from 195°C to 141°C.

<u>TC-240:</u>

For TC-240 (emitter material S-80), the maximum output power occurred at cesium temperature of 220°C and collector temperature of 490°C. At cesium temperature of 180°C, the output power decreased for increased collector temperature (range 300°C - 490°C) at 1100, 1150, and 1190°C emitter brightness. Conversely, at cesium temperatures of 200 and 220°C, the output power increased for increased collector temperatures (300°C - 470°C) at 1100, 1150 and 1190°C emitter brightness.

<u>TC-241:</u>

For TC-241 (emitter material S-85), the maximum power occurred at cesium temperature of 200°C and 490°C collector temperature. At cesium temperatures from 180°C to 200°C, the output power increased for increased collector temperatures (300°C - 470°C). Also, for emitter brightness from 1100°C - 1190°C.

<u>TC-242 and TC-243</u>:

For TC-242 and TC-243 (emitter material S-70) maximum power occurred at cesium temperature 210°C and collector temperature 470°C. At 180°C cesium temperature, the output power decreased as the collector temperature was increased from 300°C to 470°C.

At cesium temperature of 200°C the output power increased for increased collector temperatures (300°C - 490°C).

VII. SLUMP REVERSAL STUDIES

Considerable insight into the process of slump or performance degradation was obtained in the course of testing TC-229. After processing and removal from the pump, this unit exhibited the following performance data:

Emitter Brightness	1100°C
Cesium Temperature	186°C
Collector Temperature	295°C
Power	0.246 watts
Voltage	0.082 volts
Current	3 amps

After approximately three hours of testing, the cell had become passive and would deliver no output power. A collector bathing technique was employed that consisted of cooling the collector and raising the cesium pressure to permit liquid cesium to continually condense onto and drip off the collector. This process was permitted to continue overnight. The following morning, the parameters were re-optimized and the following data resulted:

Emitter Brightness	1150°C
Cesium temperature	168°C
Collector temperature	276°C
Power	1.1 watts
Voltage	0.365 volts
Current	3 amps

Similar behavior was encountered with other units particularly TC-209, which was an opposed cup design using a 1/4" diameter Philips type B

emitter. The following data obtained with TC-209 is quite striking. In all cases the emitter brightness was maintained at 1150°C.

Life(Hours)	Cesium Bath	Power Density (watts/cm^2)	Percent Change
200		2.50	
2200		1.50	-40
2200	Yes	2.26	+50
3300		1.68	-26
3300	Yes	1.95	+16
4000		1.50	-23
4000	Yes	1.80	+20

Measurements of the work function of metals covered with cesium are usually carried out with surfaces that are prepared to be initially clean and in environments that are relatively free of contaminants. Furthermore, such measurements are generally conducted at elevated surface temperatures which tend to remove surface contaminants by evaporation. Surface deposits on an electrode with cesium coverage which do not readily evaporate can logically be expected to raise its work function and this process can be expected to be a continuing effect. In any cesium converter it is logical to anticipate a greater accumulation of surface contamination on the collector than the emitter because of lower evaporation rates at lower temperature. In addition, the output of a converter can be more sensitive to changes in work function of the collector than of the emitter. The impregnated type of emitter is particularly resistant to poisoning by virtue of its dispenser action.

The cesium bathing technique described above serves as a simple and effective means of removing surface contaminants from the collector.

The exact nature of the contaminants in the experiments performed under this program is not specifically known. The three likely sources are:

1. Evaporants from the emitter

2. Diffusion to the collector surface of material impurities

3. Cesium compounds formed with gaseous impurities present

Emitter evaporants are not a likely source because of long time scale of slump in cells such as TC-209 - thousands of hours as compared to high evaporation rates. Diffusion is rather unlikely because of the low operating temperatures of the collector - about 300°C. Cesium compounds formed on the surface of the collector with impurity gases is by far the most likely cause of the slump phenomenon. Furthermore, it is known that cesium oxides are soluble in liquid cesium. It is therefore reasoned that the slump reversal mechanism encountered entailed the solution of sur-face deposits such as cesium oxide in the cesium bath. This work indicates the need for cleanliness and impurity control in cesium converters.

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IX. **APPENDIX**

A) Chemical Composition of Emitter Materials Studied

Semicon Associates Inc.:

Type S-70, 30% porosity tungsten
4 Mols BaO, 1 Mol CaO, 1 Mol $Al_2 O_3$

Type S-80, 20% porosity tungsten
4 Mols BaO, 1 Mol CaO, 1 Mol $Al_2 O_3$

Type S-85, 15% porosity tungsten
4 Mols BaO, 1 Mol CaO, 1 Mol $Al_2 O_3$
(Reference 8)

Philips Laboratories:

Type B, 17% porosity tungsten
5 Mols BaO, 3 Mols CaO, 2 Mols $Al_2 O_3$
(Reference 9)

Sylvania:

Oxide Emitter, 55% $BaCO_3$, 40% $SrCO_3$, 5% $CaCO_3$
coated on a 225 nickel alloy base

B) Chemical Composition of Cesium

Dow Chemical Corporation:

Detectable Impurities		Not Detected	
Element	PPM	Element	PPM
Na	24	Ba	< 8
K	45	B	< 16
Rb	270	Cr	< 2
Al	5	Cu	< 2
Ca	10	Li	< 16
Fe	6	Ni	< 2
Mg	2	Mn	< 2
Si	29	Pb	< 2
O	36	Sn	< 8
		Sr	< 2
		Ti	< 2
		Tl	< 2

TABLE 1A

MATERIAL	REF.	RICHARDSON WORK FUNCTION ϕ VOLTS	TEMPERATURE COEFFICIENT α VOLTS/°K	TRUE WORK FUNCTION $\phi=\phi_o+\alpha T$ VOLTS	OPERATING TEMPERATURE °K	TEMPERATURE FOR CURRENT DENSITY 1 A/CM²	10A/CM²
L - Cathode	1,2,4	1.68	3.24×10^{-4}	2.13	1400	1280	1450
Impregnated Cathode Type A	1,4	1.53	5.73×10^{-4}	2.33	1400	1400	1650
Impregnated Cathode Type B	1,4	1.77	3.2×10^{-4}	2.22	1400	1220	1500
Pressed Cathode (Ba Aluminate)	1,4	1.7	3.7×10^{-4}	2.21	1400	1330	1550
Pressed Cathode (BaCa Aluminate)	1,4	1.7	3.37×10^{-4}	2.17	1400	1300	1500
Oxide Cathode	2,3	1.48	1.8×10^{-4}	1.66	1000	1050	1180
Nickel Matrix	2,5	1.07	5.6×10^{-4}	1.58	1010	1010	1200
Boriated Nickel	6	1.78	2.5×10^{-4}	2.10	1270	1270	1460
W+BaSi$_4$ (10%)	7	1.81	4.7×10^{-4}	2.15	1250	1520	1760
WC+BaSi$_4$ (10%)	7	1.71	4.6×10^{-4}	2.29	1250	1410	1650
W$_2$C+BaSi$_4$ (10%)	7	2.00	2.24×10^{-4}	2.28	1250	1360	1520
WSi$_2$+BaSi$_4$ (10%)	7	2.25	1.1×10^{-4}	2.39	1250	1450	1630
W$_2$B$_5$+BaSi$_4$ (10%)	7	2.30	4.3×10^{-4}	2.84	1250	1700	2080

24.

TABLE 1B

MATERIAL	EMISSION AT OPERATING TEMPERATURE AMPS/CM²	LIFE AT OPERATING TEMPERATURE HOURS	EVAPORATION RATE AT		
			OPER. TEMP.	1 A/CM² gm/CM²/Sec	10 A/CM²
L- Cathode	5	15,000	8×10^{-10}	10^{-11}	10^{-9}
Impregnated Cathode Type A	1	8,000	10^{-10}	10^{-10}	10^{-9}
Impregnated Cathode Type B	2.5	15,000	10^{-11}	3×10^{-13}	4.5×10^{-10}
Pressed Cathode (Ba Aluminate)	2.5	5,000			
Pressed Cathode (BaCa Aluminate)	3.5	10,000	10^{-11}	10^{-13}	10^{-10}
Oxide Cathode	0.5	5,000	4×10^{-12}		
Nickel Matrix	1	5,000			
Borlated Nickel	1	5,000			
W+BaSi$_4$ (10%)	0.04		10^{-4}	10^{-2}	
WC+BaSi$_4$ (10%)	0.12		3×10^{-7}	3×10^{-6}	
W$_2$C+BaSi$_4$ (10%)	0.12		1.2×10^{-6}	8×10^{-6}	
WSi$_2$+BaSi$_4$ (10%)	0.045		8×10^{-8}	10^{-6}	
W$_2$B$_5$+BaSi$_4$ (10%)	0.008		5×10^{-9}	7×10^{-6}	

25.

TABLE 2.

TC-173
Cylindrical
EM= S-70

Emitter Br. °C	Cesium T °C	Current Amps	Voltage Volts	Power Watts	Power Density Watts/cm^2
1100	200	.8	.2	.16	.135
1150	200	1.4	.2	.28	.24

TABLE 3.

TC-178
Cylindrical
EM= S-70

Emitter Br. °C	Cesium T °C	Current Amps	Voltage Volts	Power Watts	Power Density Watts/cm^2
1150	240	1.4	.4	.56	.47
1150	240	.8	.8	.64	.54
1150	240	.6	1.0	.60	.51
1150	240	.4	1.2	.48	.41

TABLE 4.

TC-196
Planar
EM=S-85

Emitter Br. °C	Cesium T °C	Current Amps	Voltage Volts	Power Watts	Power Density Watts/cm^2
990	200	0.2	0.4	.08	1.1
1050	200	0.4	0.4	.16	2.3
1100	200	0.6	0.38	.23	3.2
1145	200	0.5	0.6	.30	4.2
1175	200	1.0	0.4	.40	5.6
990	210	0.2	0.4	.08	1.1
1050	210	0.4	0.4	.16	2.3
1100	210	0.6	0.4	.24	3.4
1145	210	1.0	0.35	.35	5.0
1175	210	1.0	0.41	.41	5.8
1190	210	1.0	0.41	.41	5.8
990	225	0.2	0.4	.08	1.1
1045	225	0.4	0.4	.16	2.3
1100	225	0.6	0.55	.33	4.7
1150	225	1.0	0.39	.39	5.5
1200	225	1.0	0.40	.40	5.6
990	240	0.4	0.3	.12	1.7
1050	240	0.4	0.6	.24	3.4
1100	240	0.6	0.42	.26	3.7
1150	240	1.0	0.3	.30	4.3
1200	240	1.0	0.38	.38	5.4

TABLE 5.

Emitter Br. °C	Cesium T. °C	Current Amps	Voltage Volts	Power Watts	Power Density Watts/cm^2
1050	200	1.0	.80	.80	.68
1100	200	1.2	.80	.96	.82
1150	200	1.4	.72	1.01	.85
1000	225	1.2	.70	.84	.71
1050	225	1.2	.80	.96	.82
1100	225	1.0	1.0	1.0	.85

TABLE 6.

Emitter Br. °C	Cesium T. °C	Collector T. °C	Current Amps	Voltage Volts	Power Watts	Power Density Watts/cm^2
1180	160	247	4.0	.18	0.72	.57
1190	160	209	4.0	.10	0.40	.32
1205	160	209	3.0	.15	0.45	.36
1250	160	247	4.1	.40	1.60	1.26

TABLE 7.

Emitter Br. °C	Cesium T. °C	Collector T. °C	Current Amps	Voltage Volts	Power Watts	Power Density Watts/cm^2
1150	177	276	3.0	.24	.72	.57
1150	186	276	3.0	.18	.54	.43
1150	195	276	3.0	.15	.45	.35
1150	204	276	3.0	.12	.36	.28
1150	172	276	3.0	.24	.73	.58
1150	168	276	3.0	.24	.72	.57
1150	159	276	3.0	.26	.78	.61
1150	141	276	3.0	.33	.99	.78
1150	150	276	3.0	.35	1.05	.83
1150	159	276	3.0	.36	1.08	.85
1150	168	276	3.0	.365	1.10	.87
1150	177	276	3.0	.35	1.06	.83
1150	186	276	3.0	.34	1.02	.80
1150	195	276	3.0	.31	.93	.73
1150	168	276	3.0	.34	1.02	.80
1150	168	276	2.5	.385	.96	.75
1150	168	276	2.0	.46	.92	.72
1150	168	276	3.25	.315	1.02	.80
1150	168	276	3.50	.29	1.02	.80
1150	168	276	3.75	.28	1.05	.83
1150	168	276	4.0	.265	1.06	.83
1150	168	276	4.25	.24	1.02	.80
1150	168	276	4.5	.225	1.01	.79
1150	168	276	4.75	.21	1.0	.79

TABLE 7. (cont'd)

Emitter Br. °C	Cesium T. °C	Collector T. °C	Current Amps	Voltage Volts	Power Watts	Power Density Watts/cm^2
1150	168	276	5.0	.197	.99	.78
1150	168	276	3.0	.38	1.14	.90
1150	168	249	3.0	.35	1.05	.83
1150	168	258	3.0	.385	1.15	.91
1150	168	267	3.0	.40	1.2	.95
1150	168	276	3.0	.41	1.23	.97
1150	168	285	3.0	.41	1.23	.97
1150	168	294	3.0	.415	1.24	.98
1150	168	303	3.0	.418	1.25	.98
1150	168	312	3.0	.418	1.25	.98
1150	168	320	3.0	.420	1.26	.99
1150	168	330	3.0	.42	1.26	.99
1150	168	340	3.0	.418	1.25	.98
1150	168	348	3.0	.41	1.23	.97
1150	168	357	3.0	.38	1.14	.90
1150	168	366	3.0	.355	1.06	.84
1200	168	320	3.0	.52	1.56	1.24
1200	168	340	3.0	.50	1.50	1.19
1200	168	348	3.0	.50	1.50	1.19
1200	168	357	3.0	.495	1.49	1.18
1200	168	366	3.0	.495	1.49	1.18
1200	168	375	3.0	.495	1.49	1.18
1200	168	385	3.0	.49	1.47	1.17
1200	168	394	3.0	.49	1.47	1.17
1200	168	404	3.0	.49	1.47	1.17

TABLE 7. (cont'd)

Emitter Br. °C	Cesium T. °C	Collector T. °C	Current Amps	Voltage Volts	Power Watts	Power Density Watts/cm^2
1200	168	422	3.0	.485	1.46	1.16
1200	168	320	3.0	.495	1.49	1.18
1200	168	312	3.0	.495	1.49	1.18
1200	168	303	3.0	.495	1.49	1.18
1200	168	294	3.0	.495	1.49	1.18
1200	168	276	3.0	.50	1.50	1.19
1200	168	258	3.0	.50	1.50	1.19
1200	168	240	3.0	.495	1.49	1.18
1200	168	276	3.0	.535	1.61	1.27
1200	168	294	3.0	.535	1.61	1.27
1200	168	312	3.0	.53	1.51	1.20
1200	168	320	3.0	.53	1.51	1.20
1200	168	320	3.0	.55	1.65	1.31
1200	168	320	3.5	.47	1.65	1.31
1200	168	320	4.0	.435	1.74	1.38
1200	168	320	4.5	.385	1.73	1.37
1200	168	320	5.0	.335	1.68	1.33
1200	168	320	5.5	.31	1.71	1.36
1200	168	320	6.0	.275	1.65	1.31
1200	168	320	4.5	.41	1.85	1.47
1200	168	320	5.0	.355	1.68	1.33
1200	168	320	4.0	.45	1.80	1.43
1200	168	320	3.5	.50	1.75	1.39
1200	168	320	5.5	.31	1.71	1.36
1200	168	320	6.0	.275	1.65	1.31

TABLE 8.

TC-240
Cylindrical
EM=S-80

Emitter Br. °C	Cesium T. °C	Collector T. °C	Current Amps	Voltage Volts	Power Watts	Power Density Watts/cm^2
1100	180	365	1.0	.2	.2	.17
1100	180	415	.7	.2	.14	.12
1100	180	450	.3	.2	.06	.05
1100	180	475	.1	.2	.02	.02
1150	180	375	1.4	.2	.28	.23
1150	180	415	1.4	.2	.28	.23
1150	180	450	1.3	.2	.26	.22
1150	180	475	1.2	.2	.24	.20
1190	180	365	1.6	.2	.32	.27
1190	180	415	1.6	.2	.32	.27
1190	180	460	1.5	.2	.30	.25
1190	180	485	1.4	.2	.28	.24
1100	200	375	1.0	.2	.20	.17
1100	200	435	1.5	.2	.30	.25
1100	200	460	1.6	.2	.32	.27
1100	200	485	1.7	.2	.34	.29
1150	200	375	1.7	.2	.34	.28
1150	200	435	2.0	.2	.40	.34
1150	200	460	2.2	.2	.44	.37
1150	200	485	1.8	.2	.36	.31
1190	200	375	1.7	.2	.34	.29
1190	200	435	2.0	.2	.40	.34
1190	200	460	2.0	.2	.40	.34
1190	200	485	1.9	.2	.38	.32
1100	220	335	1.0	.2	.20	.17

TABLE 8. (cont'd)

EMITTER BR. °C	CESIUM T. °C	COLLECTOR T. °C	CURRENT AMPS	VOLTAGE VOLTS	POWER WATTS	POWER DENSITY WATTS/CM^2
1100	220	385	1.4	.2	.28	.24
1100	220	440	1.7	.2	.34	.29
1100	220	490	2.2	.2	.44	.37
1150	220	335	1.2	.2	.24	.20
1150	220	405	2.8	.2	.56	.47
1150	220	490	3.6	.2	.72	.61
1150	220	515	3.5	.2	.70	.59
1190	220	385	2.8	.2	.56	.47
1190	220	445	4.0	.2	.80	.68
1190	220	490	4.2	.2	.84	.71
1190	220	515	4.0	.2	.80	.68

TABLE 9.

Emitter Br. °C	Cesium T. °C	Current Amps	Voltage Volts	Power Watts	Power Density Watts/cm^2
1100	180	1.2	.2	.24	.20
1100	180	1.4	.2	.28	.23
1100	180	1.6	.2	.32	.27
1100	180	2.1	.2	.42	.35
1150	180	3.2	.2	.64	.54
1150	180	4.0	.2	.80	.67
1150	180	4.4	.2	.88	.74
1150	180	4.8	.2	.96	.81
1190	180	6.0	.2	1.20	1.04
1190	180	7.6	.2	1.52	1.28
1190	180	8.0	.2	1.60	1.36
1190	180	8.4	.2	1.68	1.43
1100	200	2.4	.2	.48	.41
1100	200	2.4	.2	.48	.41
1100	200	3.2	.2	.64	.54
1100	200	3.6	.2	.72	.61
1150	200	5.2	.2	1.04	.85
1150	200	6.4	.2	1.28	1.08
1150	200	6.6	.2	1.32	1.12
1150	200	7.2	.2	1.44	1.22
1190	200	4.0	.2	.80	.67

TABLE 10.

TC-242
Cylindrical
EM=S-70

Emitter Br. °C	Cesium T. °C	Collector T. °C	Current Amps	Voltage Volts	Power Watts	Power Density Watts/cm^2
1100	190	320	3.2	.2	.64	.54
1100	190	320	2.0	.4	.80	.67
1100	190	425	4.0	.2	.80	.67
1100	190	425	2.8	.4	1.12	.86
1100	190	460	4.6	.2	.92	.78
1100	190	460	3.0	.4	1.20	1.02
1150	200	325	1.6	.2	.32	.27
1150	200	325	1.2	.4	.48	.41
1150	200	455	2.8	.2	.56	.47
1150	200	455	1.6	.4	.64	.54
1100	200	325	1.6	.2	.32	.27
1100	200	325	1.2	.4	.48	.41
1100	200	460	2.4	.2	.48	.41
1100	200	460	1.0	.4	.40	.34
1100	200	510	1.6	.2	.32	.27
1100	200	510	.08	.4	.32	.27
1100	210	470	4.0	.2	.8	.67
1100	210	470	3.0	.4	1.2	1.02

<div align="center">

TABLE 11.

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<div align="right">
TC-243
Cylindrical
EM=S-70
</div>

Emitter Br. °C	Cesium T. °C	Collector T. °C	Current Amps	Voltage Volts	Power Watts	Power Density Watts/cm²
1100	180	280	1.6	.2	.32	.27
1100	180	445	1.2	.2	.24	.20
1150	180	315	2.0	.2	.40	.34
1150	180	445	1.6	.2	.32	.27
1150	200	335	6.4	.2	1.28	1.08
1150	200	465	6.4	.2	1.28	1.08
1150	200	520	4.8	.2	.96	.81
1100	200	335	4.8	.2	.96	.81
1100	200	465	5.2	.2	1.04	.85

<div align="center">

TABLE 12.

</div>

<div align="right">
TC-222
Metal Ceramic
EM=Philips Type"B"
</div>

Emitter Br. °C	Cesium T. °C	Collector T. °C	Current Amps	Voltage Volts	Power Watts	Power Density Watts/cm²
1150	173	255	3.0	.25	.75	.59
1175	173	260	5.1	.23	1.17	.93
1190	173	255	6.35	.22	1.40	1.11
1220	173	260	6.3	.31	1.95	1.55

TABLE 13.

CELL #	GEOMETRY	EMITTER TYPE	EMITTER AREA CM^2	EMITTER BR. °C	CESIUM TEMP. °C	POWER DENSITY WATTS/CM^2
TC-173	Cylindrical	*S-70	1.18	1150	200	0.24
TC-178	Cylindrical	S-70	1.18	1100	240	0.60
TC-195	Cylindrical	Oxide** Triple Carbonate	1.18			
TC-196	Planar	S-85	0.07	1150	225	5.50
TC-EC3	Cylindrical	S-85	1.18	1150	200	0.84
TC-222	Metal Ceramic Opposed Cup	Philips Type "B"	1.27	1190	173	1.10
TC-225	Metal Ceramic Opposed Cup	S-85	1.27	1180	170	0.86
TC-229	Metal Ceramic Opposed Cup	S-85	1.27	1150	168	0.99
TC-235	Cylindrical	S-80	1.18			
TC-240	Cylindrical	S-80	1.18	1190	220	0.71
TC-241	Cylindrical	S-85	1.18	1150	200	1.22
TC-242	Cylindrical	S-70	1.18	1100	210	1.02
TC-243	Cylindrical	S-70	1.18	1150	200	1.08

*S-Designates Semicon Types

**Sylvania Type

37.

EMITTER

COLLECTOR

.010

.125

$\frac{3}{4}$

$\frac{1}{8}$

$\frac{1}{4}$
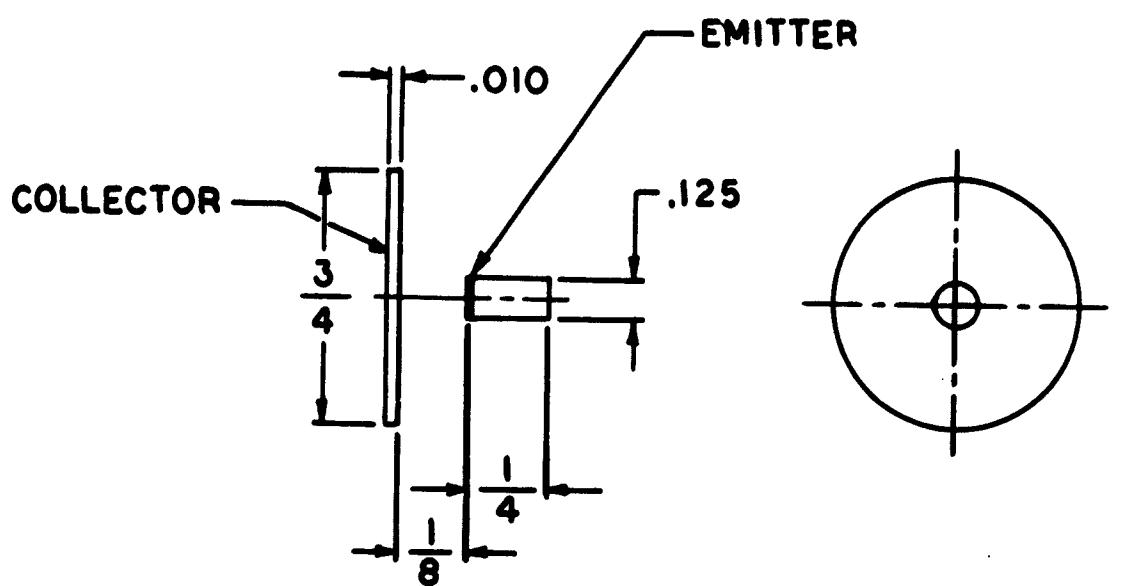
FIGURE 1   PLANAR GEOMETRY
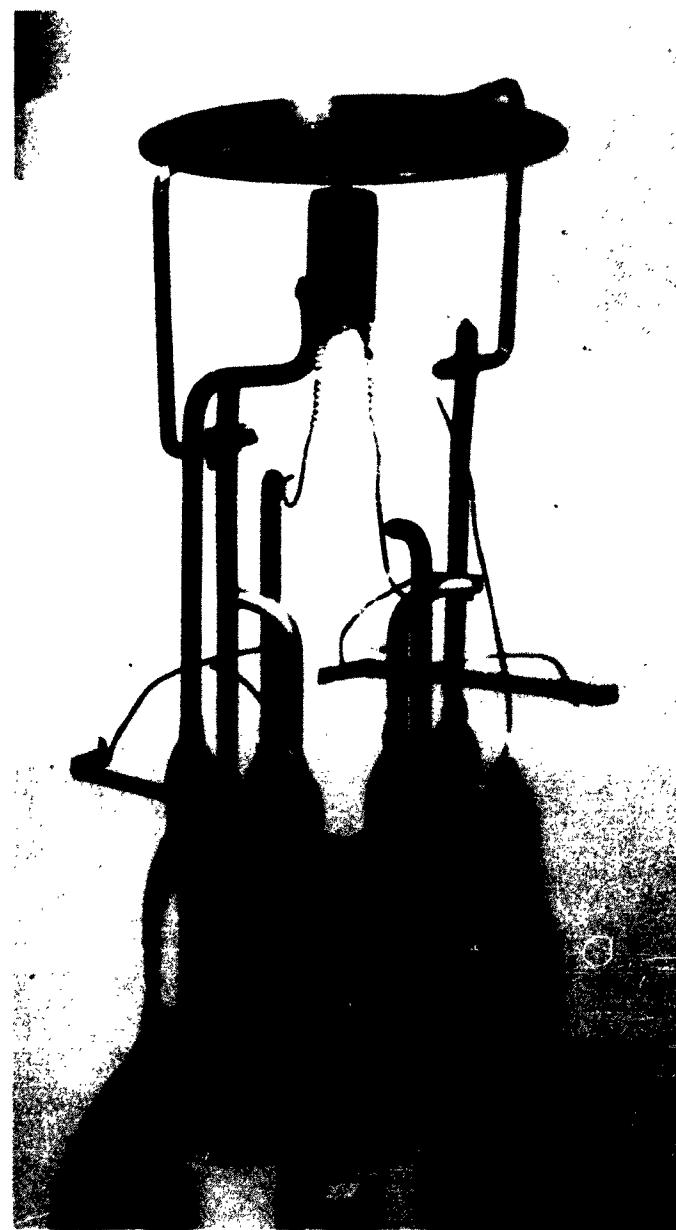
FIGURE 2   PLANAR GEOMETRY ASSEMBLY

.118 DIA
± .001

$\frac{3}{8} \pm \frac{1}{64}$

.156 DIA
± .001
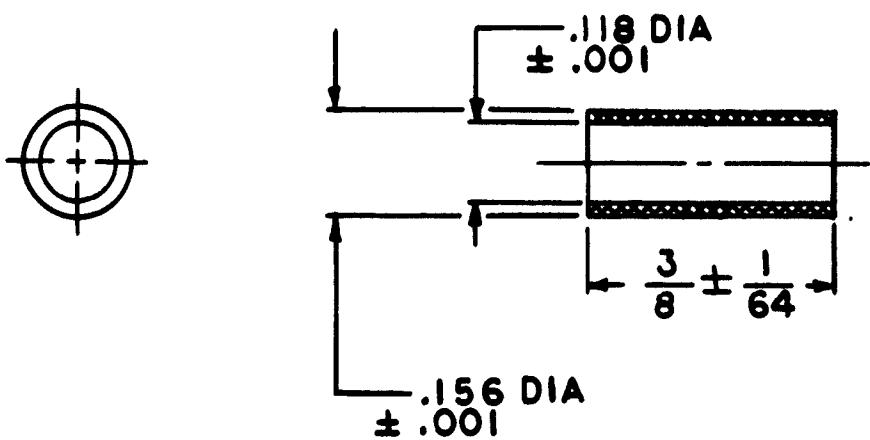
FIGURE 3A   CYLINDRICAL EMITTER

COLLECTOR

EMITTER

.156

$\frac{3}{8}$

$\frac{3}{8}$

$\frac{3}{8}$

$\frac{9}{16}$

A

.010

A

SECTION A A
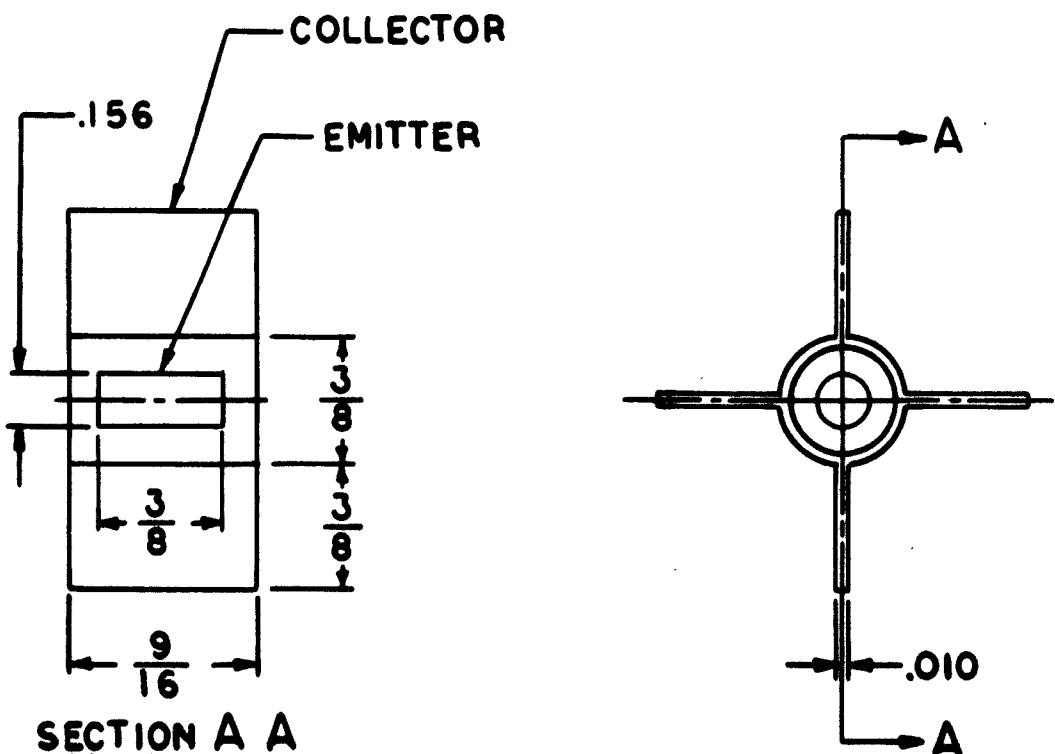
FIGURE 3B   CYLINDRICAL GEOMETRY

.118 DIA ±.001

$\dfrac{3}{8} \pm \dfrac{1}{64}$

.156 DIA ± .001
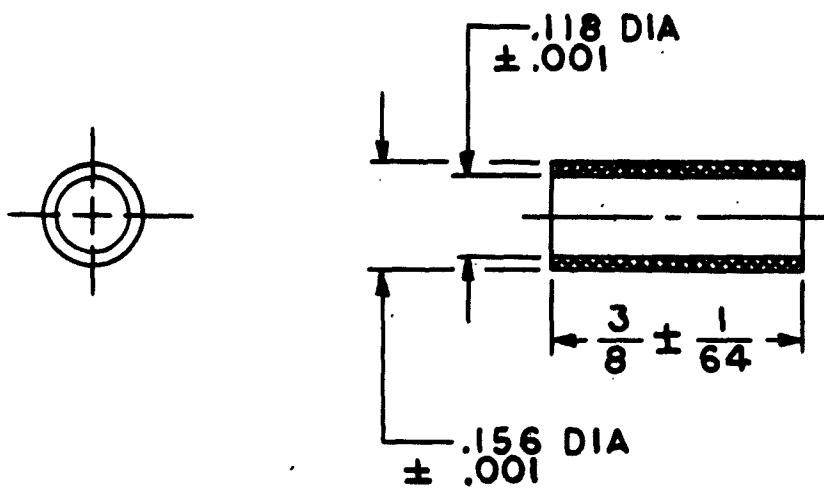
FIGURE 4A CYLINDRICAL EMITTER

COLLECTOR

EMITTER

.156

$\dfrac{3}{8}$

$\dfrac{3}{8}$

$\dfrac{3}{8}$

$1\dfrac{1}{4}$

A

A

.010

SECTION A-A
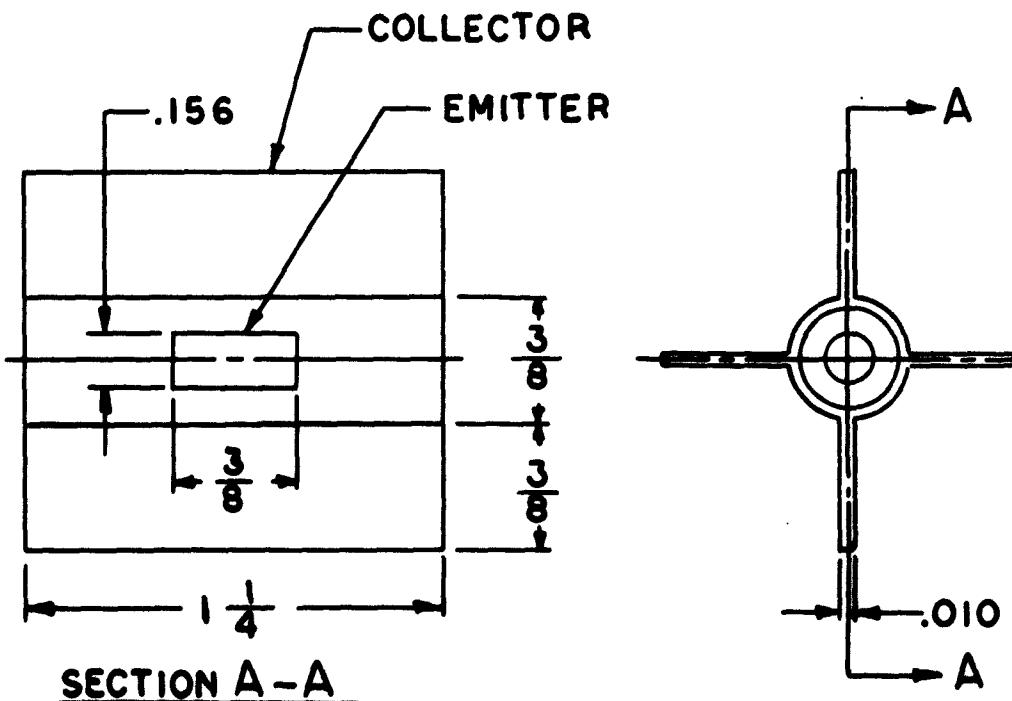
FIGURE 4B CYLINDRICAL GEOMETRY

.118 DIA
± .001

$\frac{3}{8} \pm \frac{1}{64}$

.156 DIA
± .001
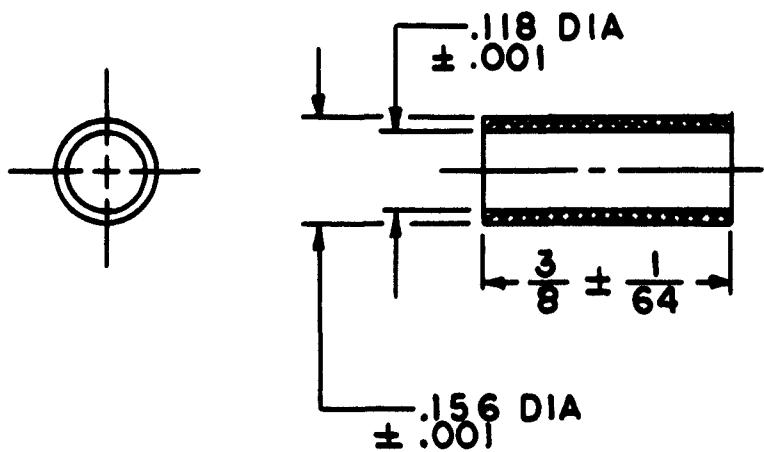
FIGURE 5 A   CYLINDRICAL EMITTER

.156

COLLECTOR

EMITTER

$\frac{3}{8}$

$\frac{1}{2}$

$\frac{3}{8}$

$1\frac{1}{2}$

SECTION A-A

A

.010

A
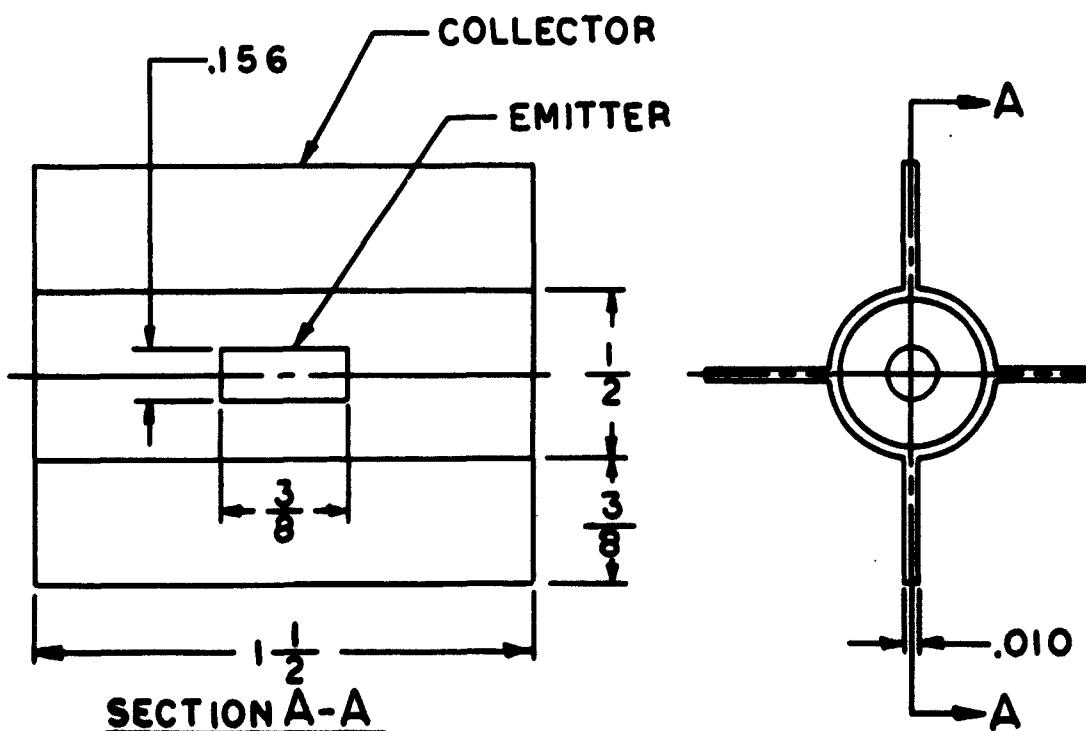
FIGURE 5 B   CYLINDRICAL GEOMETRY
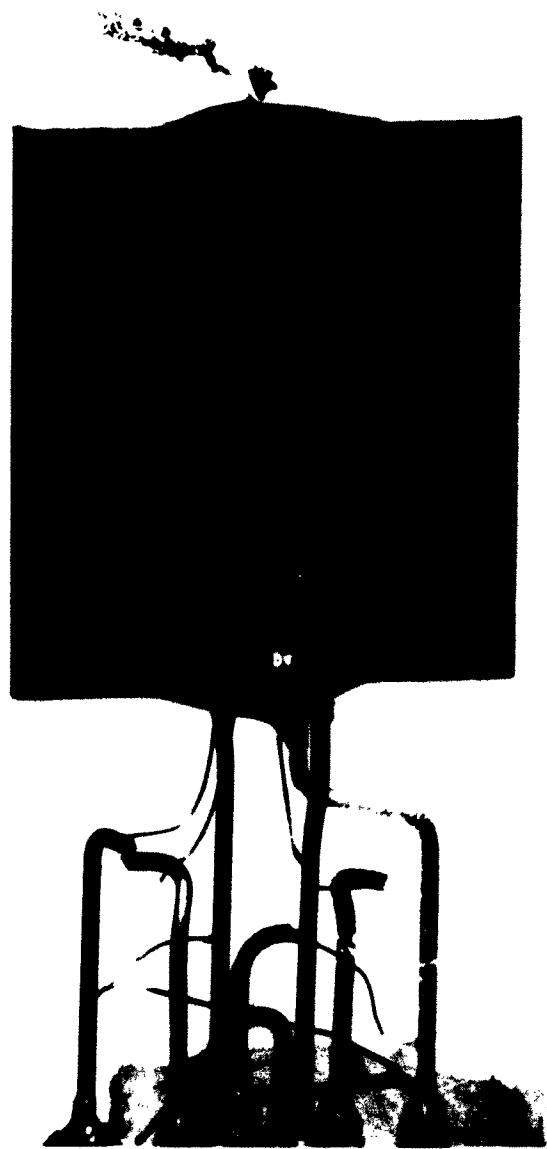
FIGURE 6   CYLINDRICAL GEOMETRY ASSEMBLY
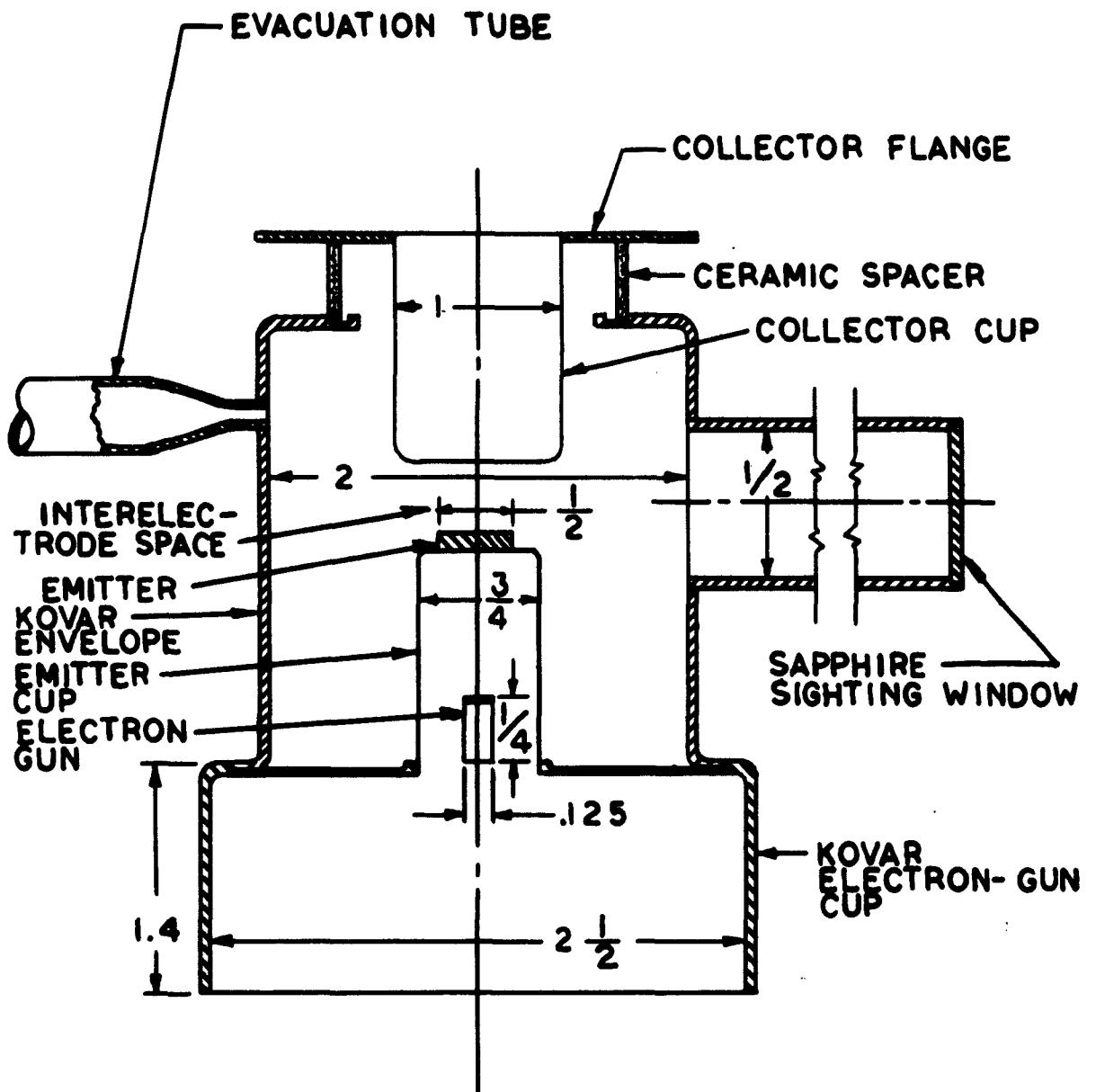
FIGURE 7 OPPOSED CUP METAL-CERAMIC GEOMETRY

FIGURE 8   OPPOSED CUP METAL CERAMIC ASSEMBLY
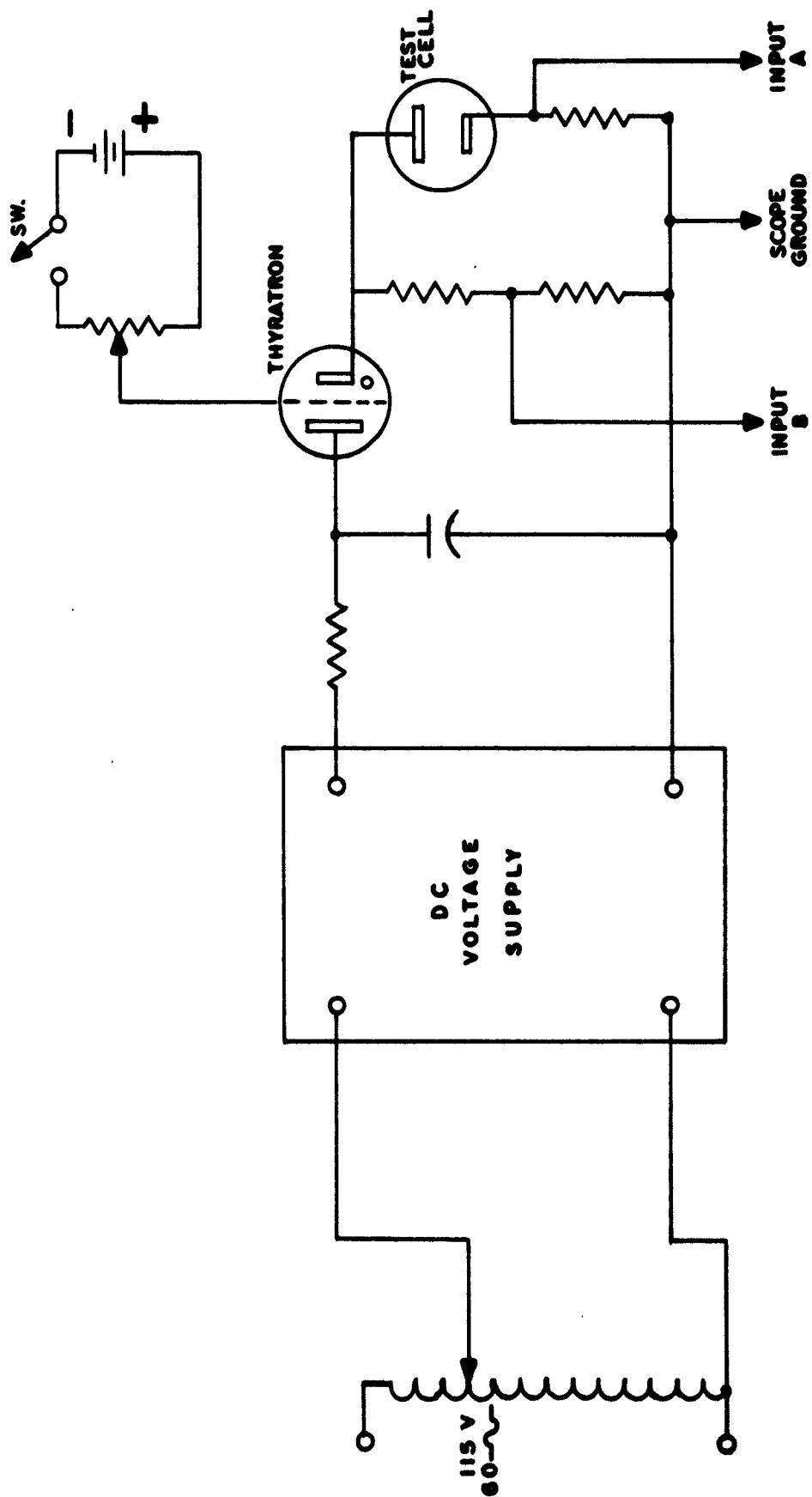
FIGURE 9 CIRCUIT DIAGRAM FOR MEASURING VACUUM EMISSION
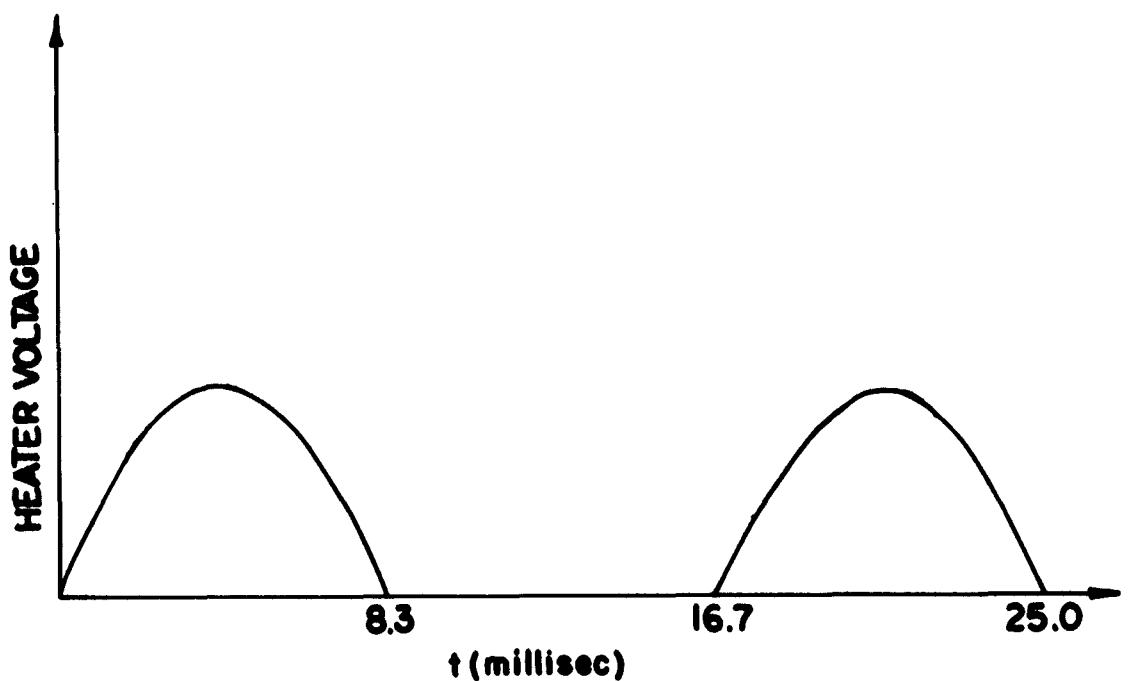
FIGURE 10A HEATER VOLTAGE VS TIME
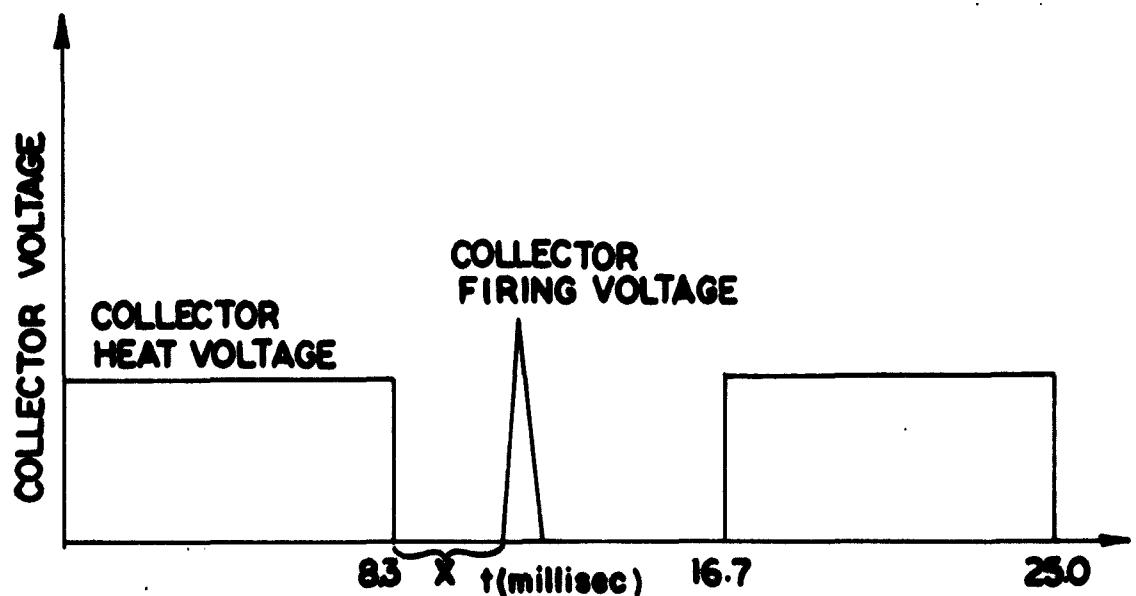
NOTE: X IS A VARIABLE DELAY WITH A RANGE FROM 0 TO 8.3MS

FIGURE 10B COLLECTOR VOLTAGE VS TIME
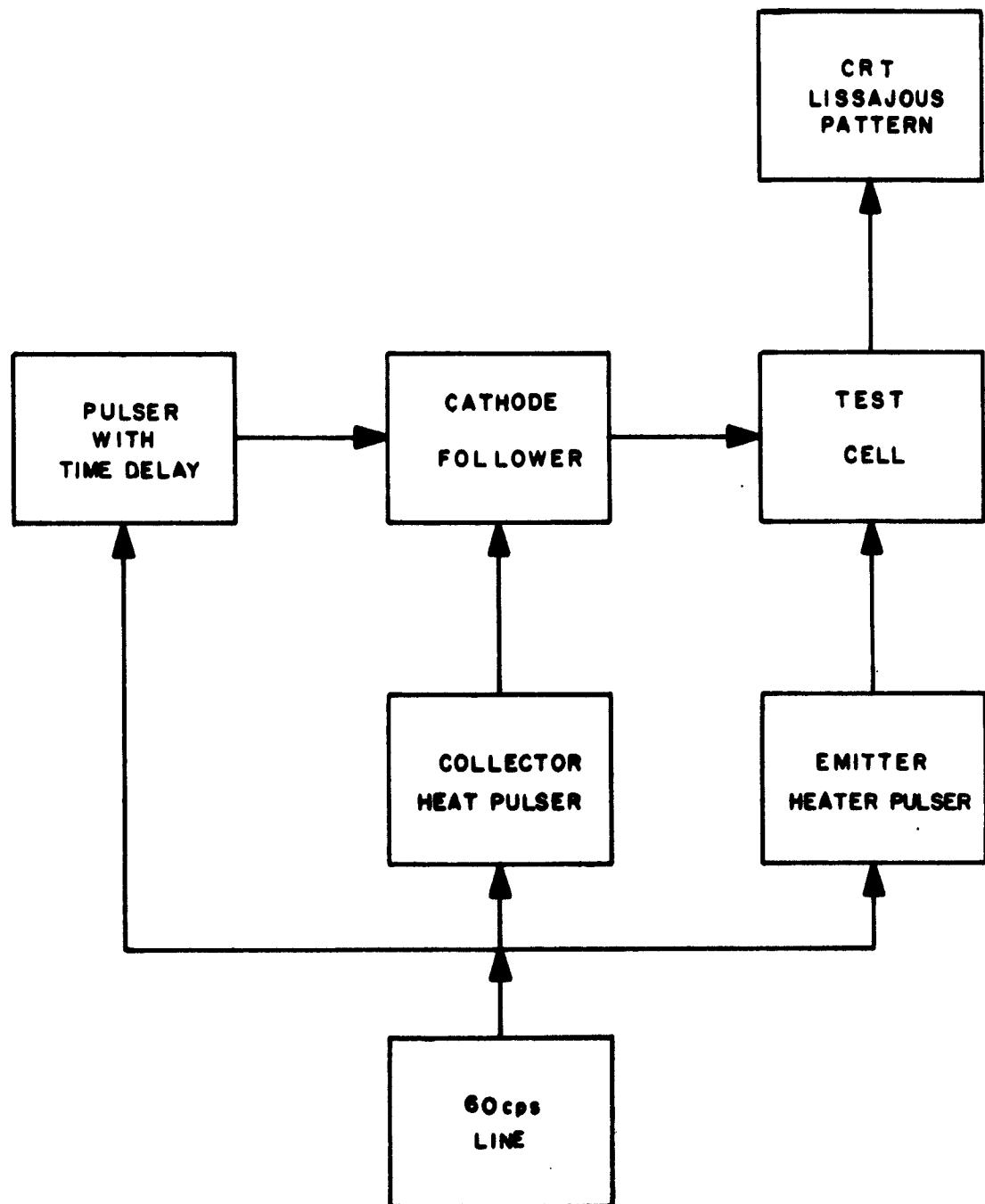
FIGURE II SIMPLIFIED BLOCK DIAGRAM OF
THERMIONIC CELL EVALUATION CIRCUITRY
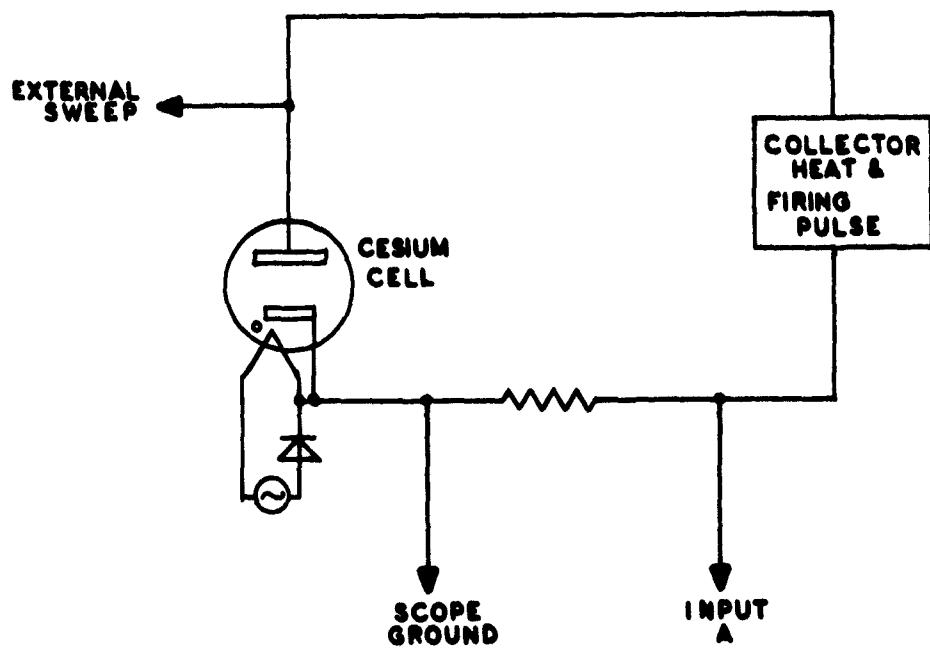
FIGURE 12 CIRCUIT DIAGRAM FOR I vs V PULSE TESTING

ELECTRON
GUN
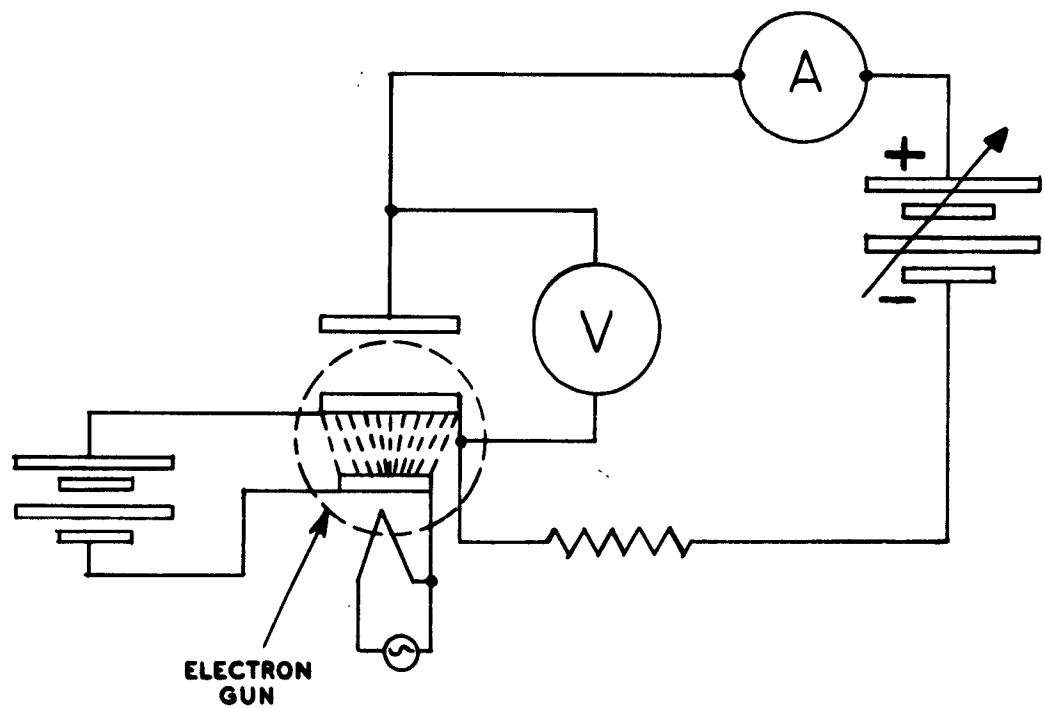
FIGURE 13 CIRCUIT DIAGRAM FOR D C TESTING OF CELL
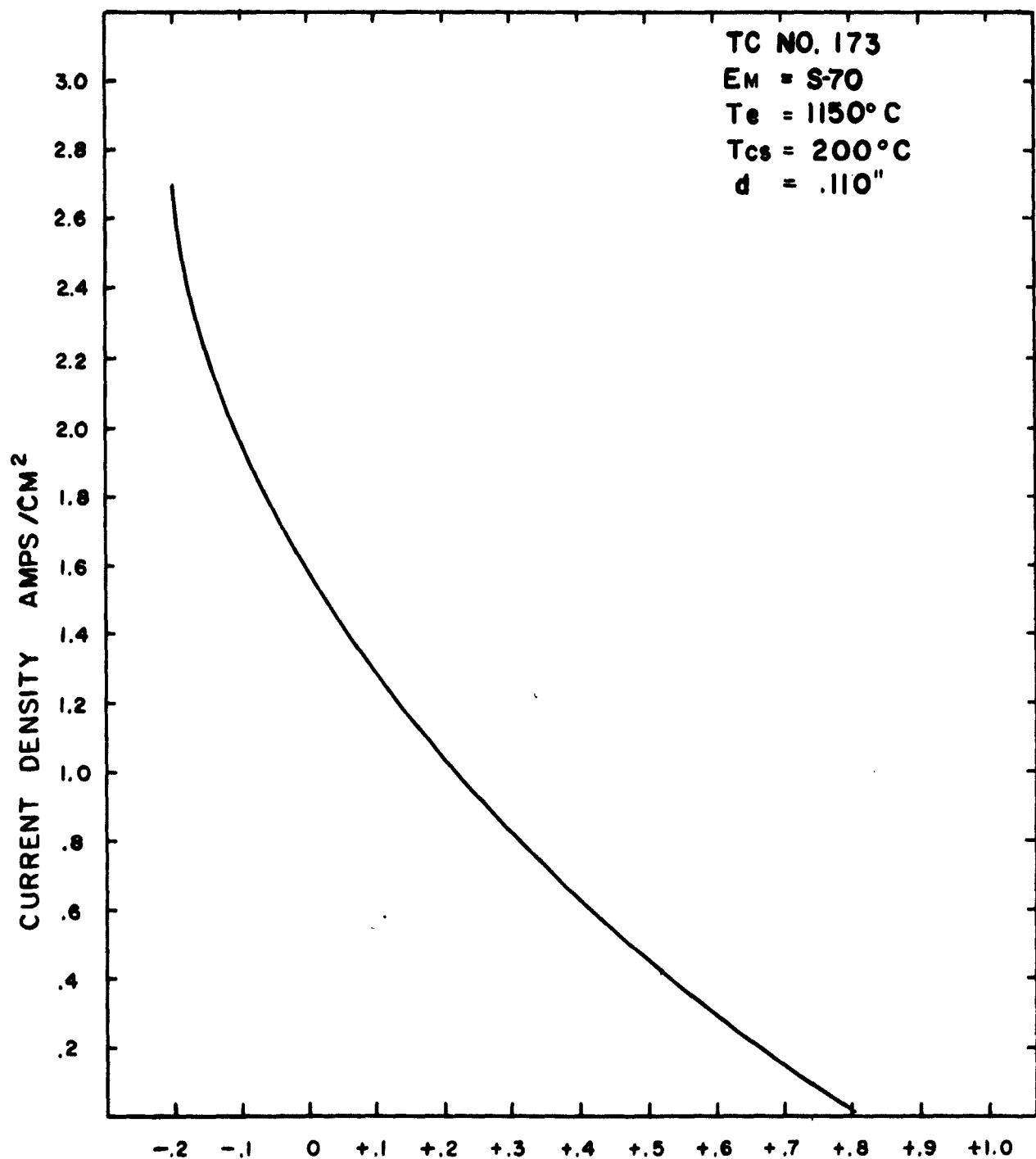
FIGURE 14   CURRENT DENSITY VS OUTPUT VOLTAGE
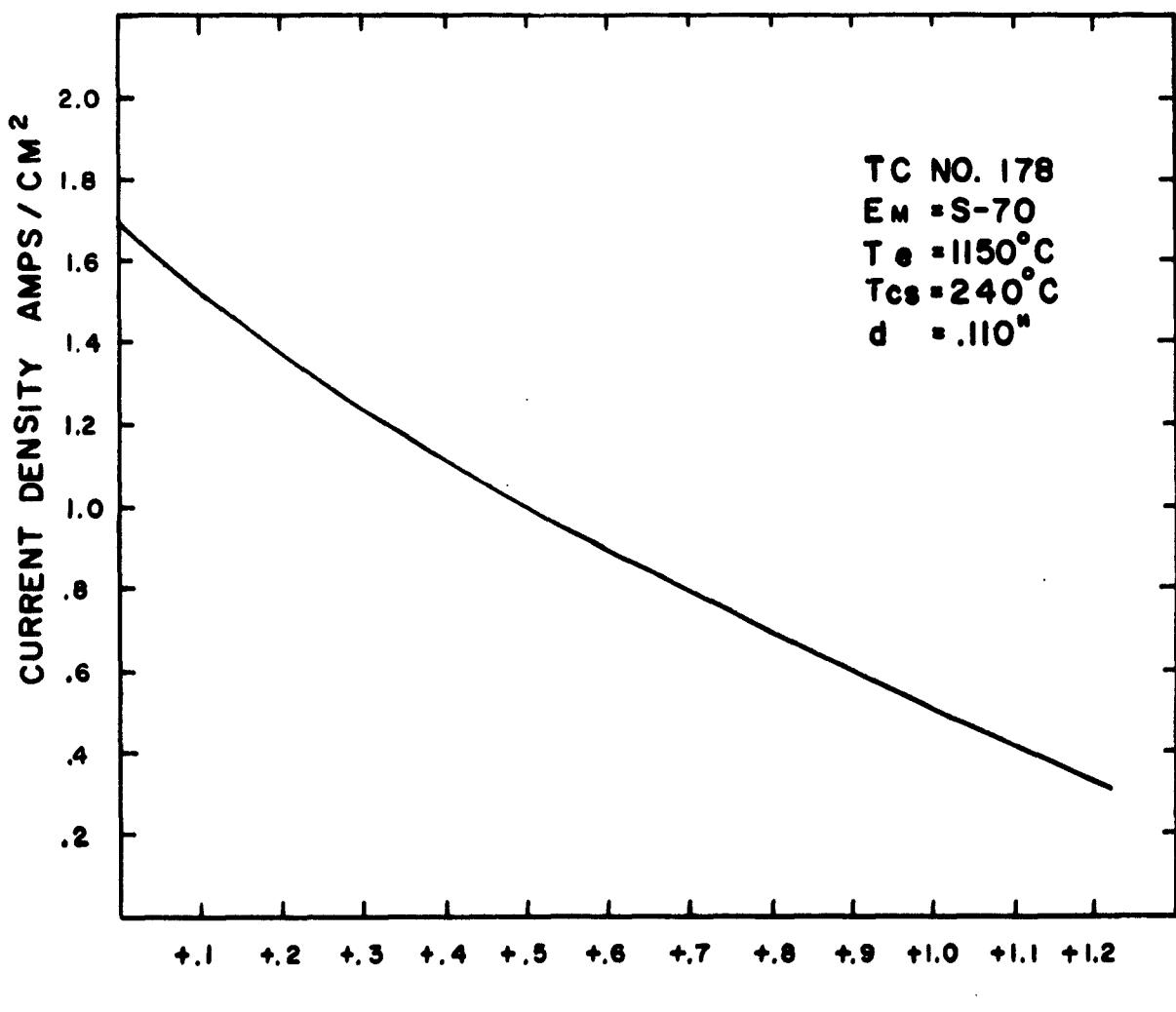
FIGURE 15   CURRENT DENSITY VS OUTPUT VOLTAGE

TC NO. EC3
Em = S-85
Te = 1150°C
Tcs = 200°C
d = .172"
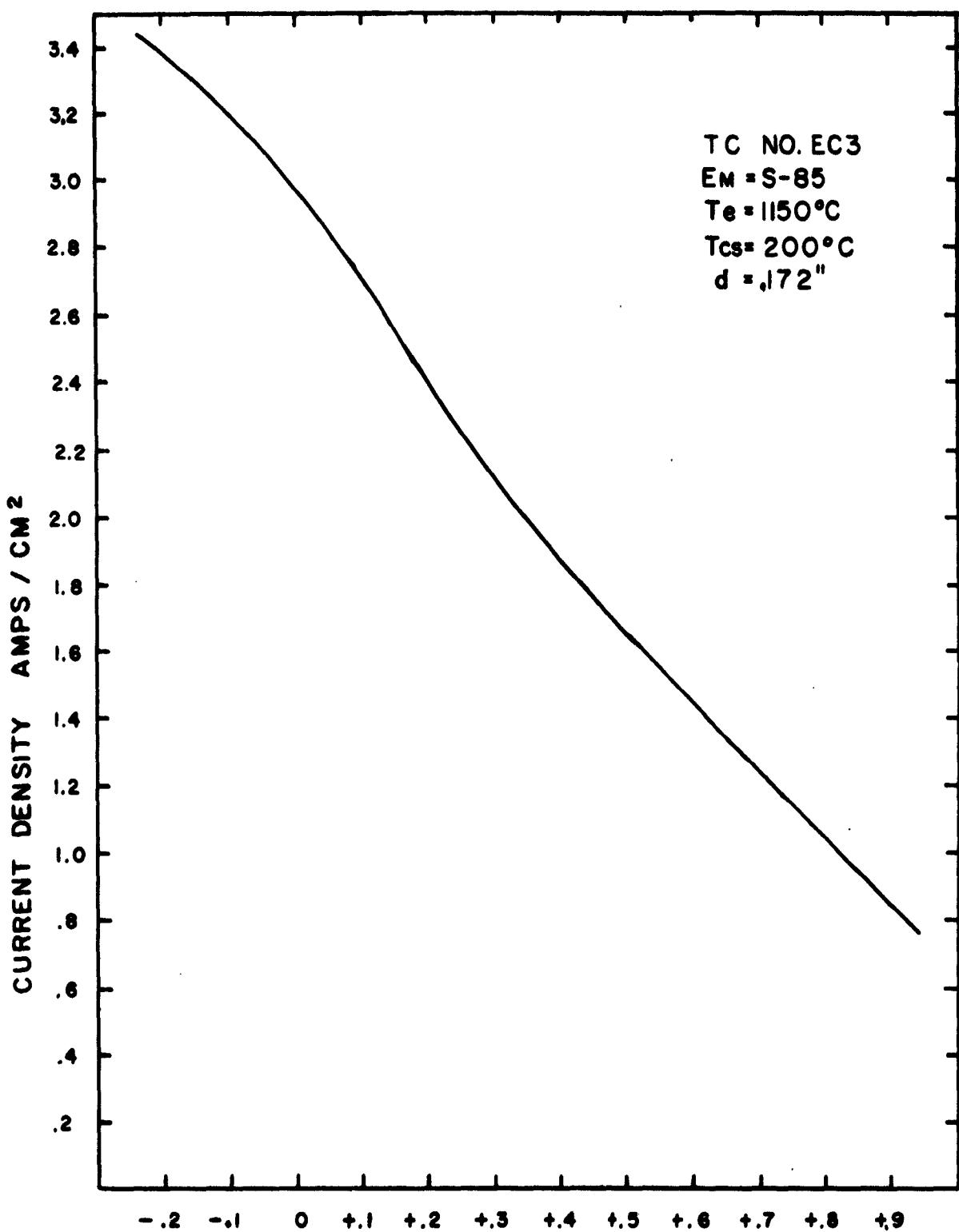
OUTPUT VOLTAGE-VOLTS

FIGURE 16   CURRENT DENSITY VS OUTPUT VOLTAGE

TC NO. 195
E$_M$ =CCC
Te =980°C
Tcs=200°C
d =.110"
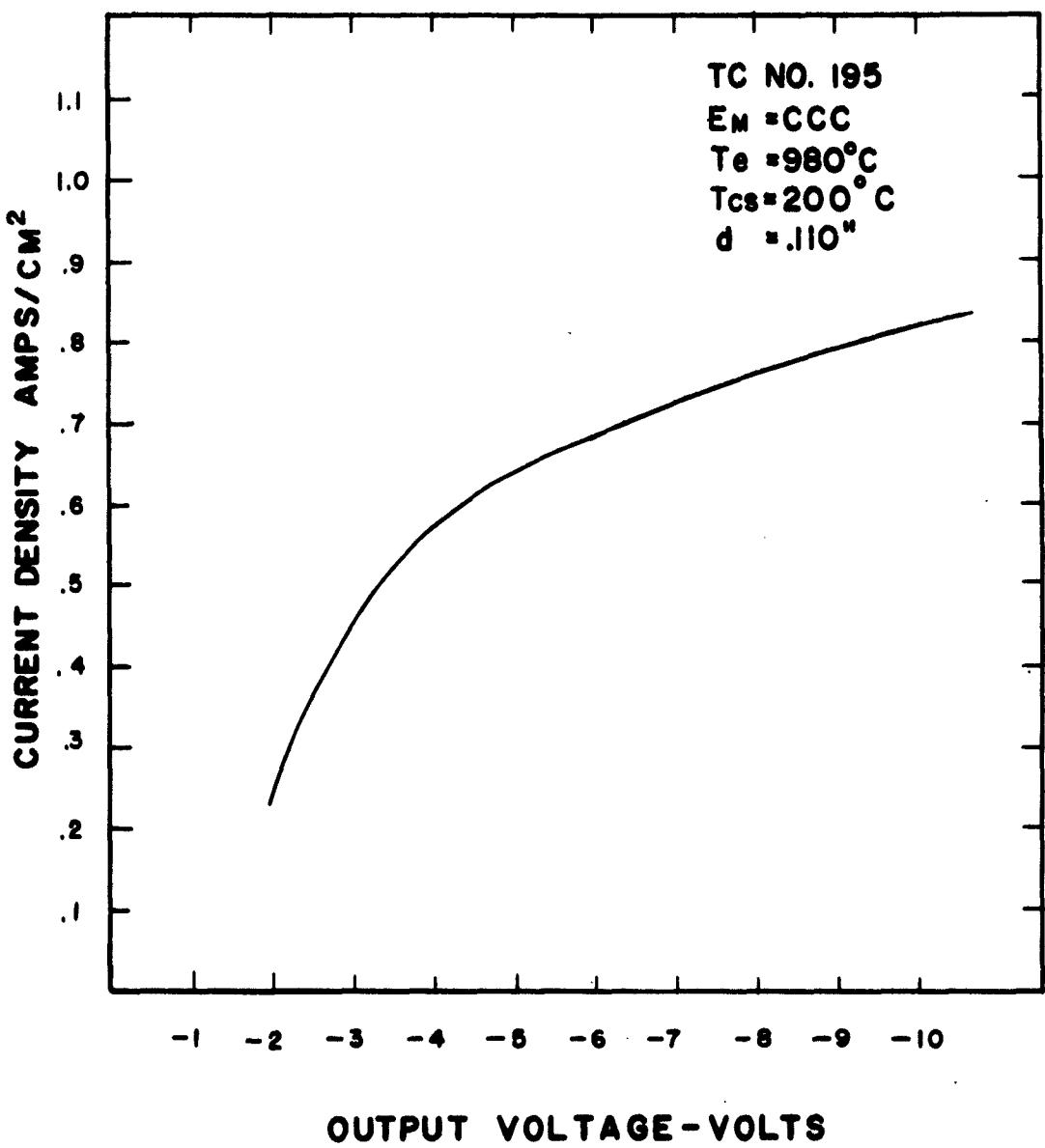
FIGURE 17   CURRENT DENSITY VS OUTPUT VOLTAGE
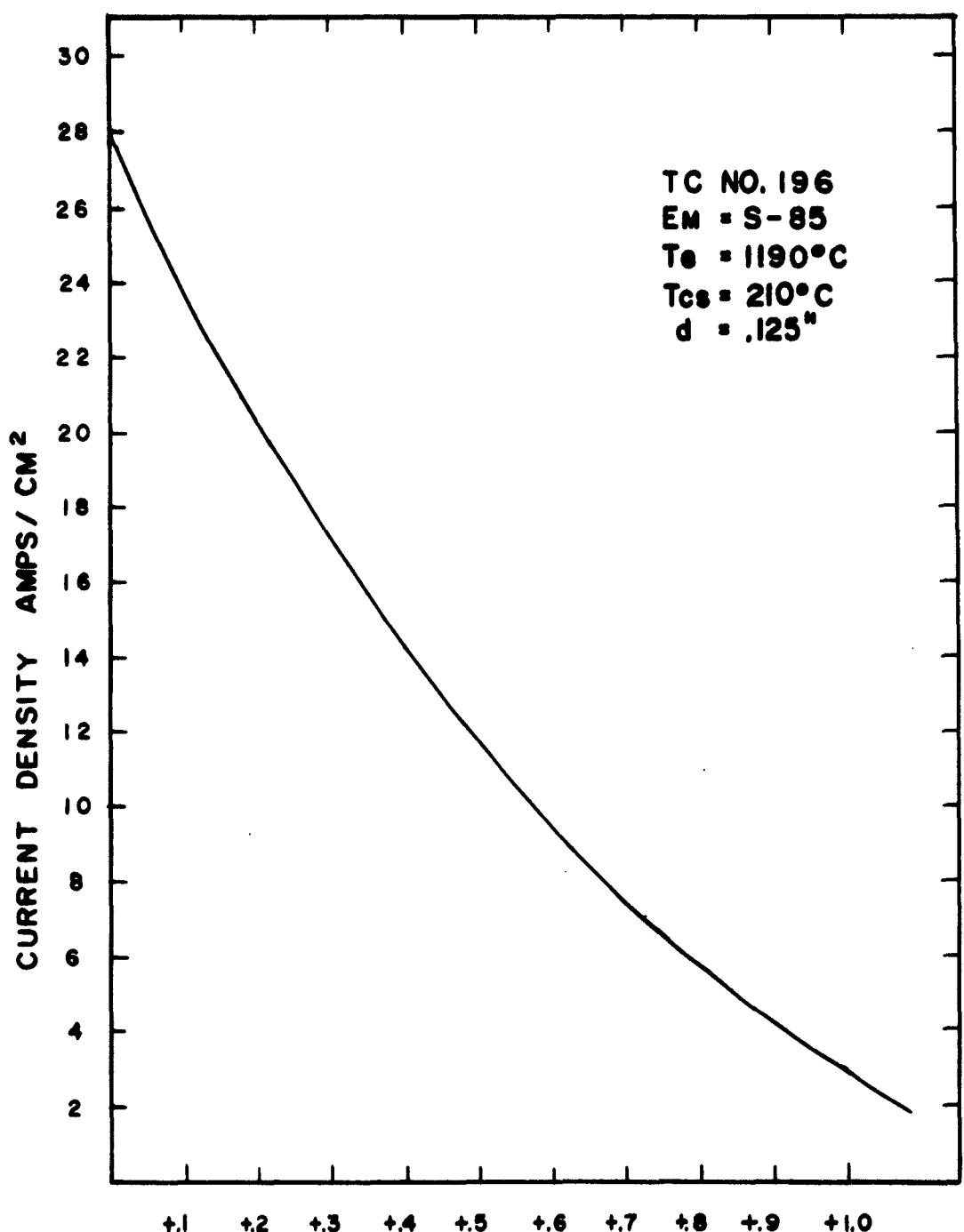
FIGURE 18   CURRENT DENSITY VS OUTPUT VOLTAGE

TC NO. 229
Eм = S-85
Te = 1150°C
Tcs = 168°C
Tc = 276°C
d = .175"
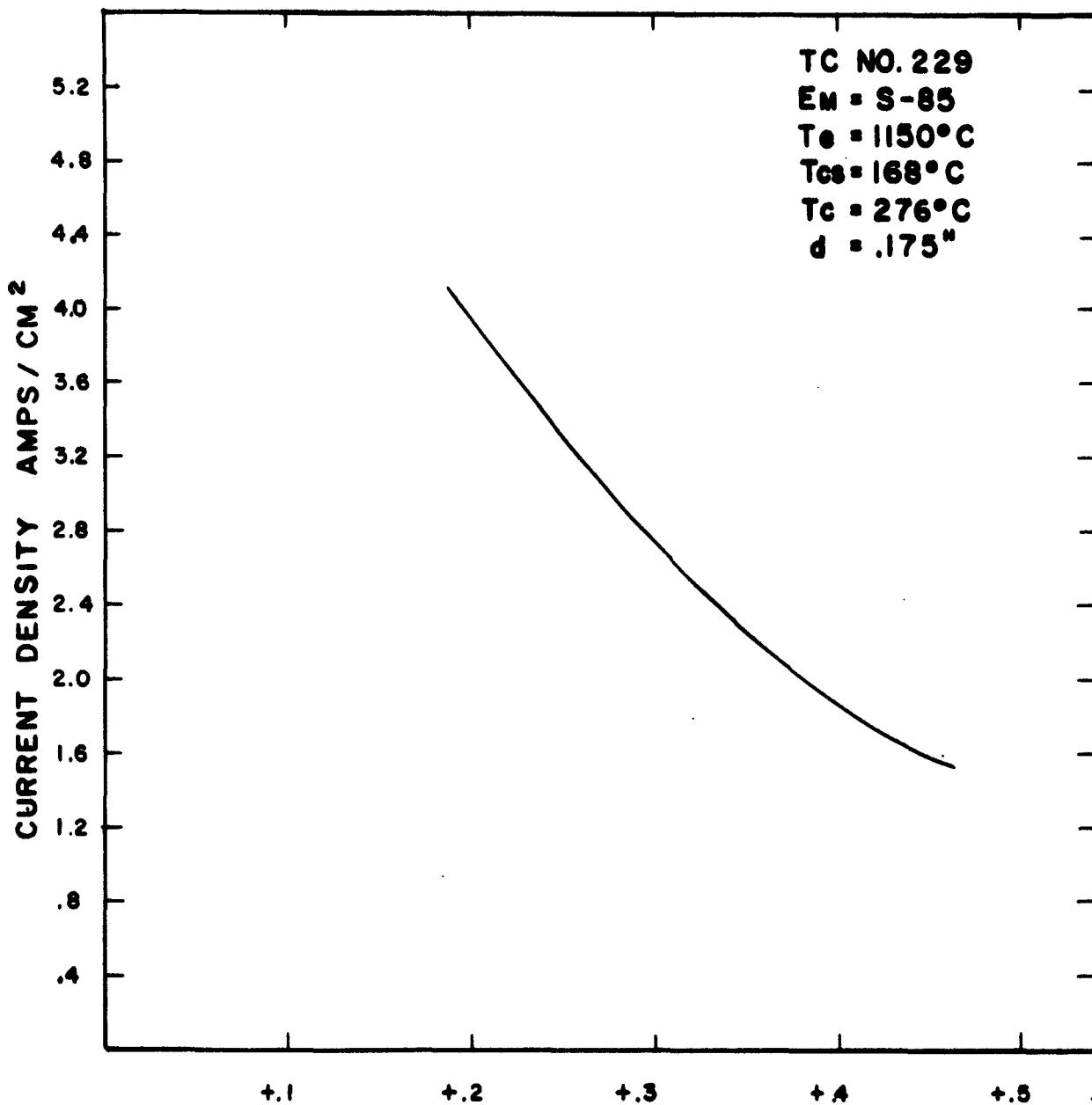
FIGURE 19   CURRENT DENSITY VS OUTPUT VOLTAGE

TC NO. 240
Em = S-80
Te = 1190 °C
Tcs = 220 ° C
Tc = 490 ° C
d = .175 "

OUTPUT VOLTAGE-VOLTS
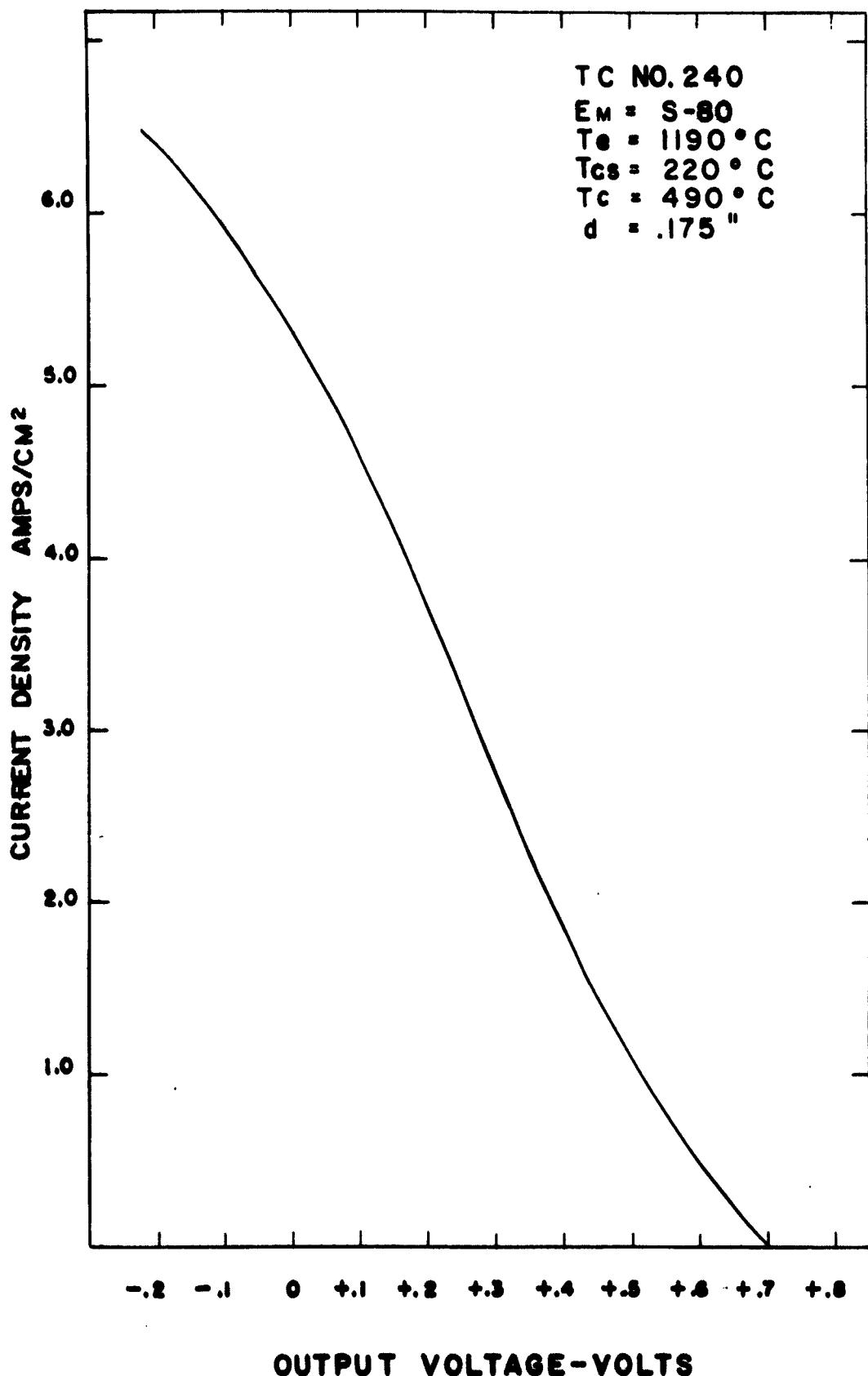
FIGURE 20 CURRENT DENSITY VS OUTPUT VOLTAGE
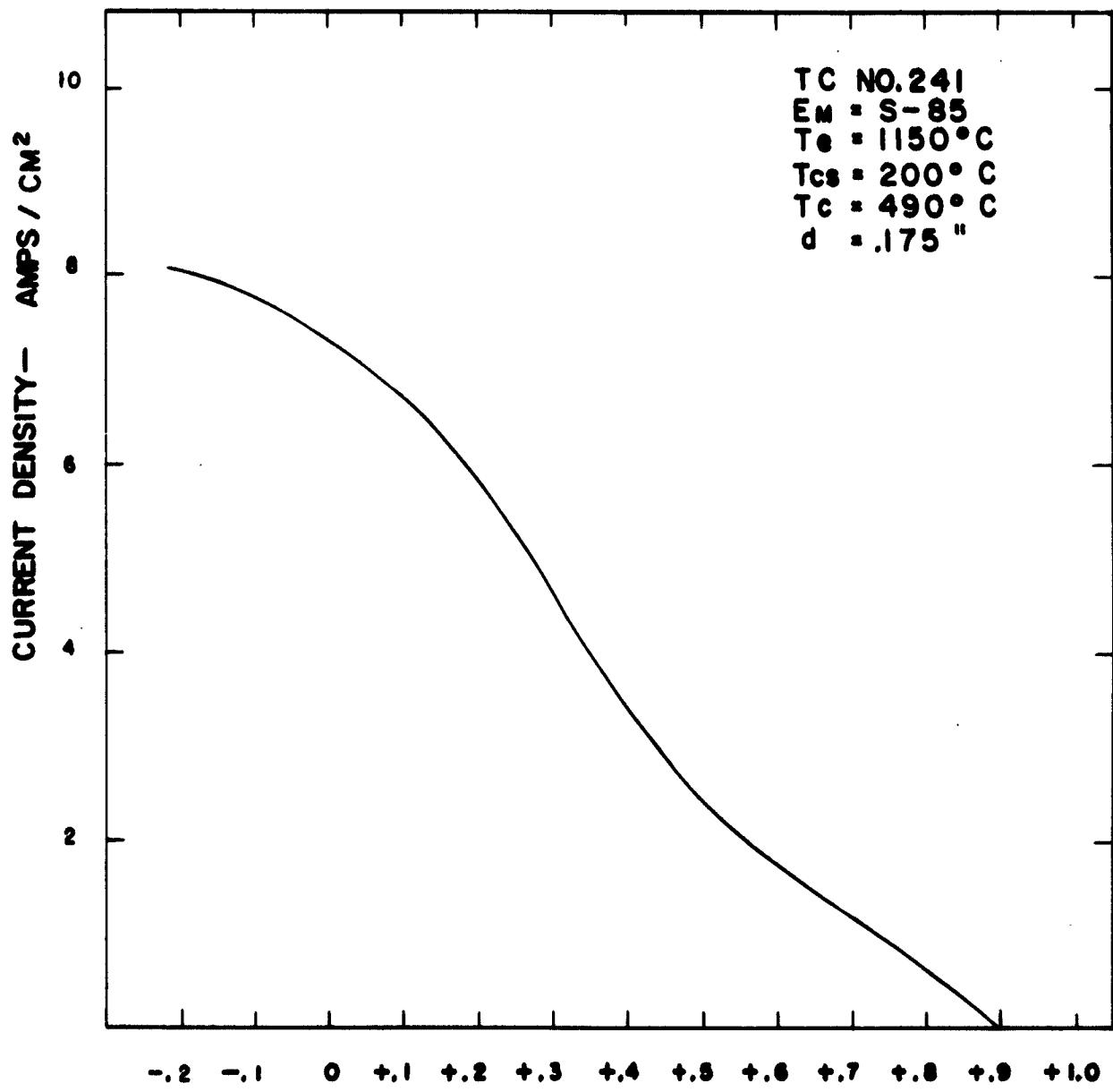
FIGURE 21   CURRENT DENSITY VS OUTPUT VOLTAGE

CURRENT DENSITY - AMPS / CM²

OUTPUT VOLTAGE-VOLTS

T C NO. 242
E ᴍ = S-70
T e = 1100C
Tcs = 210 °C
T c = 470 °C
  d = .175 ⁿ
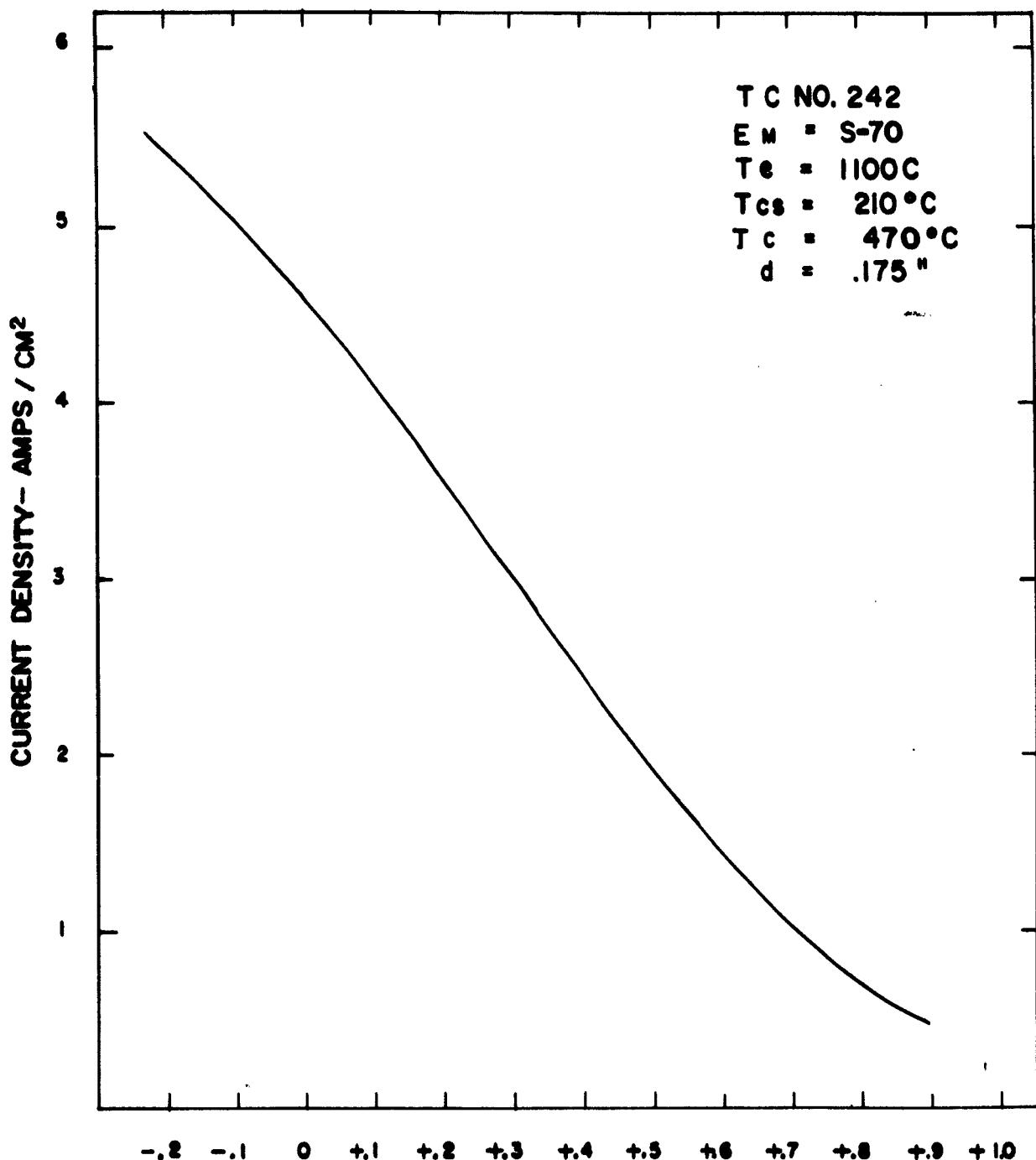
FIGURE 22   CURRENT DENSITY VS OUTPUT VOLTAGE
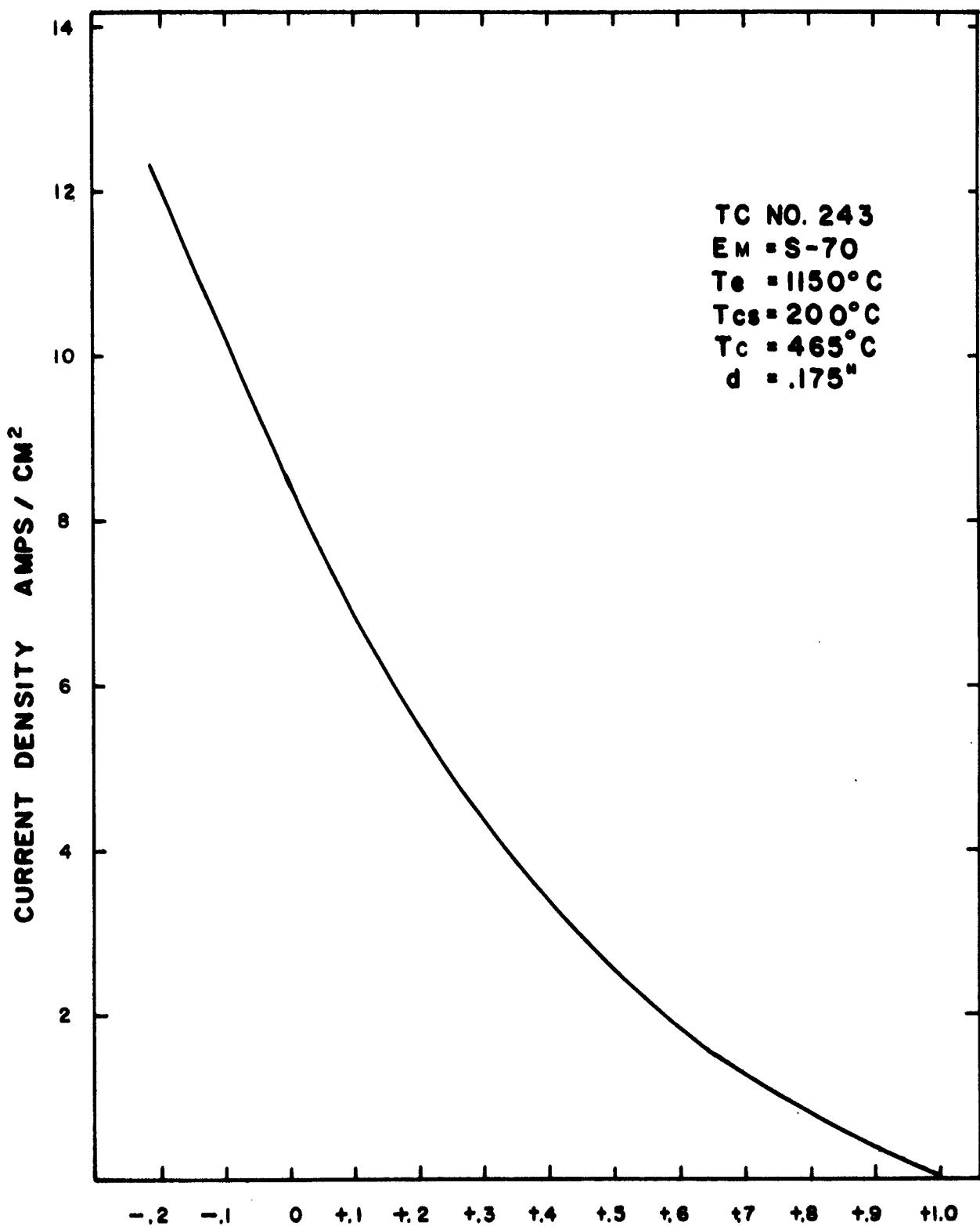
FIGURE 23 CURRENT DENSITY VS OUTPUT VOLTAGE

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